


CONSERVATION SCIENCE IN MEXICO'S NORTHWEST

ECOSYSTEM STATUS AND TRENDS IN THE GULF OF CALIFORNIA




Elisabet V. Wehncke, José Rubén Lara-Lara,
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This book is dedicated to the memory of
Laura Arriaga Cabrera, Salvador Contreras-Balderas,
and Daniel Lluch Belda, caring colleagues,
great scientists, and exceptional human beings
to whom Baja California and the Gulf of California
owe so much.

Dedicamos este libro a la memoria
Laura Arriaga Cabrera, Salvador Contreras-Balderas y
Daniel Lluch Belda, colegas comprometidos,
grandes científicos, y seres humanos excepcionales,
a quienes Baja California y el Golfo de California
tanto les deben.

TABLE OF CONTENTS

INTRODUCTION

Elisabet V. Wehncke, José Rubén Lara-Lara, Saúl Álvarez-Borrego, and Exequiel Ezcurra

The history of Baja California and the Gulf of California is one of evolution in isolation. It is a natural account of the deep causes of the diversity of life on Earth. All along the Gulf the driving theme is insularity: During the last six million years the Gulf of California has kept the long and dry peninsula separated from the Mexican mainland, and the Peninsula of Baja California has maintained the Gulf literally submerged in its own depths, sequestering it from the Pacific Ocean. On this landscape of sea and land that mutually embrace each other, keeping in solitude the genetic secrets of their founding life forms, smaller patches of insularity are superimposed at even smaller scales. Marine islands surround the Peninsula on all sides, and high mountains, true sky islands in a desert sea, imprint the landscape all the way from the U.S. border down to Los Cabos. Palm oases in deep, disjunct canyons form yet again thousands of wetland islands within the rocky matrix of the peninsular ranges. The seacoast is fringed by coastal lagoons that repeat in a fractal manner the isolation theme in smaller and smaller bodies of water.

These patches of segregation are the driving force of biological speciation, of adaptation to local conditions and specialization to particular isolated environments. After millions of years, fragmentation yields unique life forms. It also yields unique cultures. Quite separated from the rest of Mesoamerica, the Cochimí Indians developed here one of the most incredible assemblages of cave paintings in the world. Later, during the Spanish colony, the Jesuit fathers founded here their own Utopia in a system of missions that evolved in complete independence from the hard and cruel rules of the mainland *conquistadores*. True to the etymology of the word, the Peninsula has been indeed almost an island. Even in recent decades, the remarkable Mexican journalist Fernando Jordán referred to Baja California as "the other

Mexico" (*el otro México*). It has always been a land of fantasy and adventure, a territory of surprising, often bizarre growth-forms, and of immense natural beauty.

At present, however, modern transportation, population growth, urban sprawl, agricultural technology, and modern fishing techniques, among other causes, seem to be putting stress on the fragile peninsular environment. This book is an attempt at discussing some of the issues related to environmental degradation and natural resource conservation in the region within a regional perspective.

BIOLOGICAL UNIQUENESS

Few places show the extraordinary environmental heterogeneity of the Peninsula of Baja California and of the Gulf of California. The regional climates vary from mediterranean-type winter rains in the north, to monsoon-type summer rains in the south. The steep slopes of the mountain ranges generate some of the most dramatic environmental gradients on Earth. The northern part of the Peninsula extends from a coastal sclerophyllous scrub in the west, to a dry subtropical desert in the east, with a sequence of mediterranean scrubs (chaparral) and temperate pine-oak forests covering, respectively, the intermediate and the highest altitudes of the central mountain ranges. A rare form of tropical deciduous forest occupies the lowlands of the Cape Region, in the southern part of the Peninsula. Also in the Cape region, but in higher elevations, temperate pine-oak forests are found in the mountains of the Sierra La Laguna. This unique temperate ecosystem—a relictual memory of past glaciations—has evolved in extreme isolation, and is composed mostly of rare, highly endemic species. Similar areas of geographic isolation and biological rarity are found in the central mountain ranges (San Francisco, Guadalupe, and La Giganta), and in the oceanic islands of the Gulf of California and of the Pacific coast.

The flora of Baja California contains an extraordinarily high proportion (almost 30%) of endemic species. Endemism (*i.e.*, the property of being uniquely restricted to a small area) is particularly high in the island ecosystems of the region, both in the Pacific and the Gulf of California, and in the isolated *sierras* such as San Pedro Martir, Juárez, La Libertad, San Francisco, Guadalupe, and La Laguna. Similar levels of endemism are found in reptiles and land mammals, 22% of which are endemic.

Even in the case of birds, which by their volant nature are more cosmopolitan, the region of Southern California and Baja California harbors 11 strictly endemic species and 114 endemic subspecies: 2% of the avian species richness is endemic, and a remarkable 22% of the diversity at the subspecies level is unique to the region. Extinction is already a major threat for many avian species. The Guadalupe storm petrel (*Oceanodroma macrodactyla*), a rare and highly endemic marine bird, has already become extinct, and so have some seven other local, very restricted subspecies.

In the same way as the Peninsula is isolated from the Mexican mainland by the Gulf of California, the Sea itself is also a sort of "marine peninsula", isolated from the rest of the Pacific by the 1,500 km of land of Baja California. Biologically, the Gulf of California –also known as Mar de Cortés– is one of the most productive and diverse seas in the world, harboring some 4,900 known invertebrate species (excluding the single-celled protozoans), with a very high level of endemism (Brusca 2010). Some authors estimate that a similar amount of invertebrate species remains undescribed in this extraordinarily rich environment. A similar situation of exceptionally high diversity is found in marine fishes. Around 911 species have been recorded in the Gulf, 86 (10%) of which are endemic to the region. Of these, teleostean fishes comprise some 750 species. Reef fishes, in general, have more restricted distributions than deep-sea, pelagic, or sandy shore species. Of 271 known reef fishes in the Gulf of California, some 52 species (19%) are endemic to the region. The Gulf is also extremely rich in marine mammals, harboring 36 species. Of these, 31 are cetaceans, including the highly endemic *vaquita* porpoise (*Phocoena sinus*) that is only found in the Upper Gulf (Brusca 2010).

The high diversity of the Gulf of California is largely due to two phenomena: (a) the great variety of general habitats that are found in the Gulf, including mangrove swamps, coastal lagoons, coral reefs, shallow and deep sea basins, hydrothermal vents, and a diverse array of shore and subtidal substrates; and, (b) the complex geological and oceanographic history of the Gulf, including past invasions of animal immigrants from Tropical South America, the Caribbean Sea (before Earth's tectonic forces sealed the Panama seaway), the cold shores of California (during past glacial periods), and across the vast stretch of the Pacific Ocean from the Tropical West Pacific. The Gulf is important both biologically and economically. It houses an inordinately high proportion of the marine species richness of Mexico, and yields some 30% (*ca.* 600,000 tons) of the catch of national fisheries. The sustainable use and the conservation of the Gulf of California are critical issues under both points of view.

THE SOCIOECONOMIC BACKGROUND

The region is not only one of Mexico's richest areas in terms of natural resources; it also holds one of Mexico's fastest growing regional economies. The *maquiladora* industries in Tijuana, the high-input crops and associated agro-industries in the agricultural valleys (Mexicali, Valle de Guadalupe, San Quintín), and the growing tourism industry, are all powerful driving forces of economic and demographic growth. Indicators of economic development show values that suggest a relatively high economic development compared to the rest of Mexico. Globally, the Peninsula of Baja California has levels of illiteracy of less than 4%, the number of houses with electricity approaches 90%, and the mean number of live children per woman over 12 years is around 2.4 (for comparison purposes, the State of Oaxaca in southern Mexico has 17% of illiteracy, only 73% of its houses have access to electricity, and the mean number of live children per woman above 12 years of age is 3.1). The *per capita* contribution of the peninsular inhabitants to the GDP is more than 20% above the national average. However, the success of the peninsular economy has brought a large demographic increase to the region, mostly derived from internal migration within Mexico, from the impoverished southern States into the more dynamic economy of Baja California.

This fast demographic and economic growth poses some pressing environmental problems to the region: On the one hand, it is extremely difficult to keep adequately supplying services such as running water and sewage to cities that double in size every ten years. Rapid demographic growth means, almost by definition, an increasing lag in water and electricity supply, and in sanitary infrastructure, including poor drainage and lack of water-treatment facilities, with the concomitant results of pollution and environmental degradation. On the other hand, rapid growth means an ever-increasing demand for freshwater, fisheries, and other natural resources, many of which are scarce in the Peninsula, chiefly due to the aridity of the region. Thus, the rapid expansion of the peninsular population is mostly done at the expense of depleting underground aquifers, degrading coastal wetlands, and of destroying the natural ecosystems and the watersheds that surround the large urban conglomerates.

AIMS AND SYNTHESIS

Both the Mexican government and the conservationist non-governmental organizations (NGOs) have developed actions to protect the incredibly rich and increasingly endangered ecosystems of Baja California. The region harbors now a large number of protected natural areas. Since 1993 there has been an immense effort to decree and protect new areas. Significant efforts have been also developed to promote the sustainable use of fisheries and ocean natural resources in general. Many of these advances are discussed in detail in different chapters of this book.

However, and despite the progress achieved, it is difficult to say at this time if the increasing pace of conservation efforts in Mexico is being able to stall the environmental degradation that the region is suffering. The optimistic note is that there seems to be in the Peninsula of Baja California and in the Gulf of California a growing awareness, as never was observed before, of the importance to take urgent action to protect the environment. The swelling number of conservation actions that have been taking place is not the sole merit of any sector. Local communities, conservation groups, research institutions, federal and state governments, NGOs, and conscientious businesspersons and eco-tourism operators have all been contributing to the growing appreciation of the environment, and to the attendant conservation actions.

It is the right moment to bring academic institutions into joint cooperative efforts to protect this land and this sea, to bring robust science into the discussion about the region's environmental future. This drives the objective of this book, to bring the academic community together in order to develop a synthesis and a vision for the Gulf of California region.

We want to thank, first and foremost, all our colleagues that made an effort to contribute to this synthesis. The edition of this book was partially funded by the David and Lucile Packard Foundation and by the Pew Fellows Program in Marine Conservation.

The Gulf of California region is part of a large ecological continuum, a large basin that involves both Mexico and the United States, with shared watersheds, species, and natural resources. The protection of these unique environments is of the uttermost importance for the survival and wellbeing of all of us, for generations to come. We hope the publication of this book may bring the perspective of science into the rich, and urgently necessary, debate about the environmental future of this extraordinary region.

REFERENCE

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ECOLOGICAL CONSERVATION IN THE GULF OF CALIFORNIA

Exequiel Ezcurra*

1. INTRODUCTION: HISTORY OF CONSERVATION EFFORTS IN THE GULF OF CALIFORNIA

In 1973, George Lindsay—one of Baja California's most eminent botanists—visited the islands of the Gulf of California together with Charles Lindbergh, Joseph Wood Krutch, and Kenneth Bechtel. Lindbergh, one of the most celebrated popular heroes of the 20th century, had become by that time a committed conservationist, interested in the preservation of whales and in the conservation of nature at large. Joseph Wood Krutch, a naturalist, had written *The Forgotten Peninsula*, one of the first natural history descriptions of Baja California. George Lindsay had helped to organize a series of scientific explorations into the Gulf of California and the Peninsula of Baja California, first from the San Diego Natural History Museum, and later from the California Academy of Sciences (Banks 1962a,b; Lindsay 1962, 1964, 1966, 1970, and Wiggins 1962). These expeditions proved to be of historic importance for conservation science. Among many other brilliant young biologists, Michael Soulé, a young doctoral student from Berkeley, invested his time on the islands studying the ecology and biogeography of lizards, testing in them many of the tenets of ecological theory that Robert McArthur had put forward (Soulé 1969; see Figure 1). The influence of the region on him was profound: Two decades later, Soulé reached international fame applying the tenets of island biogeography he had developed in the Gulf of California islands to the revolutionary creation of a new branch of science he called Conservation Biology (Soulé 1986).

Kenneth Bechtel, a philanthropist from San Francisco, had given financial support to the Audubon Society in the 1950s–60s to study the seabird rookery at Isla

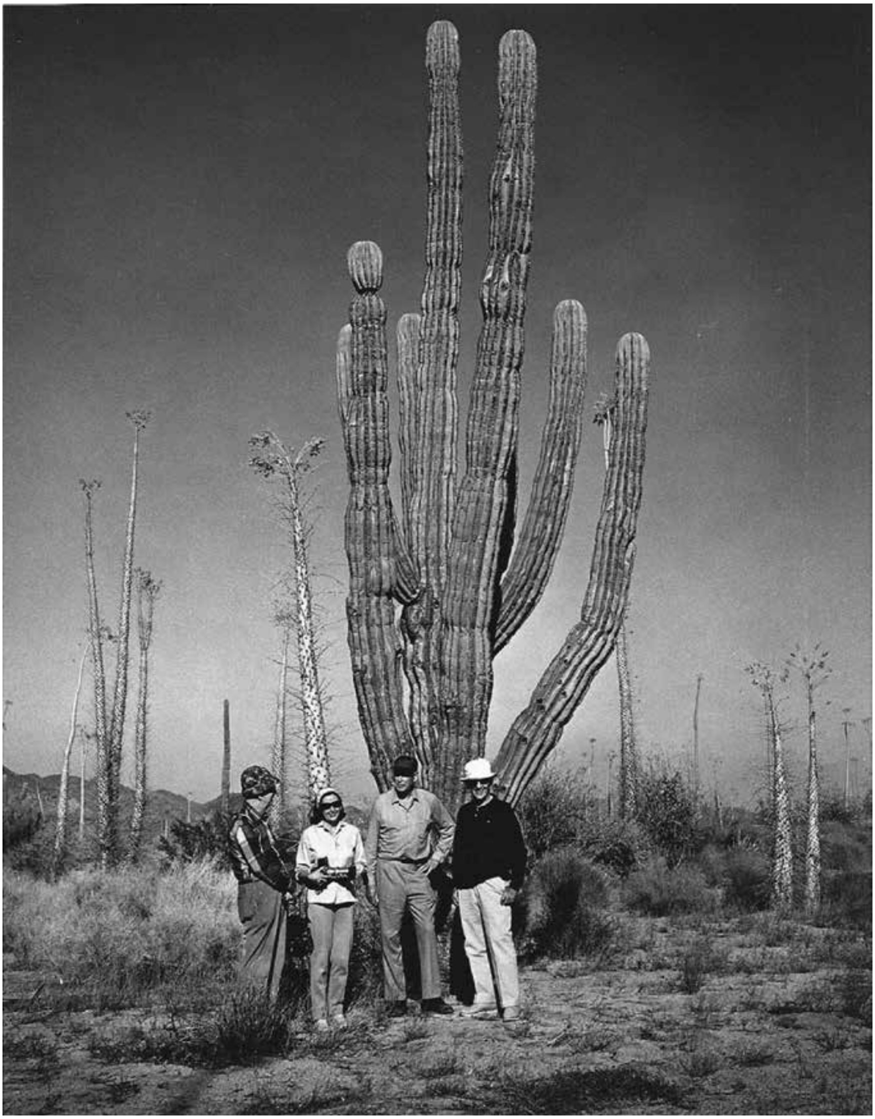

FIGURE 1. John Sloan, Chris Parrish, and Michael Soulé checking lizard traps for population studies in Ángel de la Guarda Island, near Bahía de los Ángeles, in 1963 (courtesy of the San Diego Natural History Museum archives).

Rasa, which had been decreed a protected area by the Mexican Government in 1962. Bechtel was interested in showing the Gulf of California to people who might

FIGURE 2. Joseph Wood Krutch, Nancy Bechtel, Charles A. Lindbergh, and Kenneth Bechtel in Baja California's Central Desert, near Bahía de los Ángeles in year 1969, three years before their flying boat expedition to the islands (photo taken by George Lindsay, courtesy of SDNHM archives).

be aroused by its astounding natural beauty and might help to protect it. For this purpose, he organized the trip and invited Lindbergh to visit the region (see Figure 2).

The group flew a chartered Catalina flying-boat that allowed them to get to small and remote islands. They landed in the water, and then piloted up to the beach so they could have shade under the wing. They visited many of the islands, starting from Consag north of Bahía de los Ángeles, and ending in Espíritu Santo, east of the Bay of La Paz. It was a wonderful and memorable trip.

Two or three months later, both Lindbergh and Lindsay traveled to Mexico City, to watch the Mexican premiere of a documentary film on the Gulf of California by the California Academy of Sciences that Kenneth Bechtel had sponsored. Taking advantage of the opportunity, and also of his immense popularity, Charles Lindbergh requested to see the President of Mexico, Luis Echeverría. Unfortunately, the President was abroad, on a foreign tour to Asia. The President's Private Secretary received them, possibly expecting to hear innovative ideas from Lindbergh with respect to aviation in Mexico. Much to his amazement, he heard Lindbergh raving passionately about Baja California, and very especially about the islands of the Gulf.

Later, Lindbergh called the American ambassador and asked him to organize a press conference for representatives from the Mexican media. Shortly after, the startled George Lindsay saw the editors of about five major Mexican newspapers come into their suite at the Hotel del Prado, in front of the Alameda in downtown Mexico City. The media leaders wanted enthusiastically to meet Lindbergh, expecting an interview on aviation and perhaps on Lindbergh's heroic solo flight across the Atlantic. With astonishment, they heard him preach about the immense natural wealth and the beauty of the Gulf of California.

A few months after that trip, in August 26, 1974, Charles Lindbergh died. He never saw the Gulf islands under any type of legal protection. Four years after his surprising appearance in Mexico City, however, a decree was issued protecting all of the islands of the Gulf of California. George Lindsay firmly believed that Lindbergh's intervention helped to promote the necessary governmental awareness for the decision to take place and conservation measures to ensue (SDNHM 1996). He was probably right: The slow build-up of the individual efforts of devoted conservationists and scientists has brought the islands of the Gulf of California under increasing levels of conservation. Many naturalists have devoted their best efforts to the protection of the region. This chapter will analyze some of the results of these actions.

1.1. The beginning of conservation efforts

Possibly the first conscious efforts to protect the islands of the Gulf of California started in 1951 with the publication of Lewis Wayne Walker's popular paper on the seabirds of Isla Rasa in the *National Geographic* magazine (see timeline of conservation events in Table 1). Walker was at that time a researcher at the San Diego Natural History Museum, and later became Associate Director at the Arizona-Sonora Desert Museum. He was very knowledgeable on the natural history of the region, and possessed first-hand field experience in Baja California and the islands of the Gulf of California, and especially on Isla Rasa. He wrote many popular articles on the natural history of the region, and through these publications he popularized the plight of Isla Rasa (Walker 1951, 1965).

Kenneth Bechtel (the same philantropist who later organized the flying-boat expedition described above) was at that time a trustee of the Audubon Society. In the early 1950s he donated 5,000 dollars for the preservation of Isla Rasa, starting Walker's research on Rasa, which was later also supported with a grant from

TABLE 1. Timeline of significant conservation events in the Gulf of California 1951–2014.

Year	Event
1951	Lewis Wayne Walker publishes "Sea birds of Isla Raza" in the National Geographic magazine.
1952	Kenneth Bechtel donates 5,000 dollars to the Audubon Society for the preservation of Isla Rasa, effectively setting in motion L.W. Walker's and Dr. Bernardo Villa's long-term work on the island.
1963	Tiburón Island is decreed a Wildlife Refuge and Nature Reserve by President Adolfo López Mateos.
1964	The Mexican Federal Government decrees Isla Rasa a protected "Nature Reserve and Refuge of Migratory Birds" (Reserva Natural y Refugio de Aves Migratorias).
1965	A small, two-room stone field station is built on Rasa Island as part of Dr. Villa's ongoing research and conservation work.
1967	To recover Sonoran wildlife, white-collared peccari and pronghorn antelopes are introduced to Tiburón Island by Mexico's Federal Government. The species do not prosper.
1973	In Spring, Kenneth Bechtel organizes a flying-boat expedition to the islands of the Gulf of California, with Charles Lindbergh, George Lindsay, and Joseph Wood Krutch.
1973	Inspired by the flying-boat expedition, Lindbergh and Lindsay travel to Mexico City to see President Luis Echeverría. They meet with the President's cabinet and the editors of the major Mexican newspapers, and urge them to preserve the islands of the Gulf of California.
1975	A decree is issued by President Luis Echeverría, restituting Tiburón Island to the Seri People as part of their communal property and declaring the coastal waters of Tiburón Island for the exclusive use of the Seri and off-limits for other fishermen.
1975	Bighorn sheep are introduced to Tiburón Island as a part of a federal program to study and protect the Sonoran subspecies.
1978	The Mexican Government issues a decree protecting all the islands of the Gulf of California under the category of "Wildlife Refuge" (Refugio de Vida Silvestre).
1979	Enriqueta Velarde takes over the research and conservation tasks in Isla Rasa, inspired by Bernardo Villa's pioneer work. Since then, biologists have been present in Rasa during each seabird breeding season.
1982	Mexico's first Environmental Ministry (Secretaría de Desarrollo Urbano y Ecología) is created. All natural protected areas are put under its jurisdiction.
1988	As a result of the work of Enriqueta Velarde's team, the National University of Mexico and the Federal Government publish the book Islas del Golfo de California, bringing national attention to the islands of the Gulf of California and their conservation problems.
1988	Mexico's first environmental law (Ley General de Equilibrio Ecológico y Protección al Ambiente) is passed.

Year	Event
1992	The Government of Mexico obtains a the approval of a 25-million-dollar donation from the Global Environment Fund for the management and the conservation of ten protected areas, including Islas del Golfo de California.
1993	On June 10, at Cerro Prieto near Puerto Peñasco, the President of Mexico decrees the establishment of the first marine reserve in Mexico, the Biosphere Reserve of the Upper Gulf of California and Delta of the Colorado River. This opens discussions on protecting the waters surrounding the islands in the Gulf of California.
1993	A successful program is initiated by Jesús Ramírez to eradicate introduced rats and mice from Isla Rasa using modern rodenticides.
1995	Complete eradication of introduced rodents in Isla Rasa is achieved.
1995	UNESCO's Man and the Biosphere (MAB) Program dedicates the Protected Area Islas del Golfo de California as an international Biosphere Reserve.
1995	The environmental impact statement for a hotel in Coronado Island is strongly challenged by local and national conservation and citizen groups, leading to the abandonment of the project.
1995	The Mexican company Salinas del Pacífico introduces the Baja California subspecies of the desert bighorn to Isla del Carmen. In contrast with the support that the Sonoran Bighorn program in Isla Tiburón had enjoyed, the Isla del Carmen plan is received with criticism by conservationists in the Peninsula.
1996	The Parque Nacional Bahía de Loreto is created by a Federal decree to protect the Bay of Loreto, including its five islands, from large fishing fleets.
1996	Mexico's environmental law, the "Ley General de Equilibrio Ecológico y Protección al Ambiente" is amended. The new law recognizes eight categories of natural protected areas, demanding re-categorization of all previously decreed natural protected areas into the new system.
1997	The Fund for Natural Protected Areas is created with 16.48 million dollars that still remain from GEF's original 25-million grant for ten protected areas in Mexico. The protected area Islas del Golfo de California Natural starts receiving part of the financial revenues generated by the fund, a process that ensures long-term financing for conservation.
1998	The management plan of Espíritu Santo, the first island-specific conservation plan in the Gulf of California, is completed with the joint participation of local research centers, conservation NGOs, and Ejido Bonfil. The Ejido landowners accept constraints on the development in their own insular lands.
1998	The Seri people start auctioning permits for sport hunting of bighorn sheep in Tiburón Island. Half of the proceeds go to support research, conservation and management actions, the other half goes to the Seri tribe.
1998	With the active participation and involvement of the local community, a binational group of researchers, governmental resource managers, and the Ejido Tierra y Libertad draft a management and conservation plan for the islands surrounding Bahía de los Ángeles.
2000	The Mexican Federal Government re-categorizes the islands of the Gulf of California, first established in 1978, into a Wildlife Protection Area. Administrative offices for the islands are strengthened.

Year	Event
1999	The Mexican Federal Government creates the National Commission for Natural Protected Areas (Comisión Nacional de Áreas Naturales Protegidas, CONANP) and starts seriously committing towards the conservation of natural areas.
2000 to 2010	Following the experience of the Upper Gulf, Mexico's National Commission for Protected Natural Areas starts decreeing protected waters around some of the most important islands of the region, under the category of Biosphere Reserves (Islas Marías, Isla San Pedro Mártir, Isla Guadalupe, Bahía de los Ángeles, Canales de Ballenas y Salsipuedes) or National Parks (Cabo Pulmo, Bahía de Loreto, Islas Marietas, Archipiélago de San Lorenzo, Archipiélago Espíritu Santo).
2012	On June 15, 2012, President Felipe Calderón publicly announced the cancelation of the Cabo Cortés project, and his government's commitment to the protection of the Pulmo reef. The Cabo Pulmo community had achieved one of Mexico's most noteworthy success in marine conservation.
2012	After years of conflict between developers and the citizens of La Paz, the Mexican Federal Government declares the bay of Balandra as a Wildlife Protection Area, effectively yielding to the local inhabitants who wanted to preserve this beautiful bay as part of their natural heritage.

the Belvedere Scientific Fund (also related to the Bechtel family). This financial support was shared Dr. Bernardo Villa's laboratory at the Instituto de Biología in the National University of Mexico (Universidad Nacional Autónoma de México, or UNAM; for a list of acronyms see Table 2). The funds were used to maintain a biologist and a field station on the island.

The results of these investigations soon reached the Direction of Forestry and Wildlife in the Mexican Federal Government, which in the late 1950s was headed by Dr. Enrique Beltrán, an eminent Mexican biologist and conservationist (see Figure 3). Beltrán's own interest on the issue—and the public notoriety that Isla Rasa had achieved through popular publications and through the field trips of many biologists—helped to prepare the way for the first Federal Decree protecting the insular ecosystems of the Gulf of California: In 1964 a decree was published in the official government register (Diario Oficial de la Federación) declaring Isla Rasa a Nature Reserve and a Refuge of Migratory Birds (DOF 1964).

The work at Rasa was later supported with donations from the Roy Chapman Andrews Fund at the Arizona-Sonora Desert Museum. This and other funds contributed to maintain the presence on Isla Rasa of researchers and students from Bernardo Villa's laboratory. Many of these students later became leading conservationists in the Gulf of California. Dr. Villa's work in the early 1980s effectively combined research with conservation. One of his young students at that time, Dr. Enriqueta Velarde, decided to extend the idea to other islands of the Gulf of California. With

TABLE 2. Protected Natural Areas in the Gulf of California region, classified according to their conservation category and sorted according to their date of creation.

Natural Protected Area	Date of creation	Area (ha)	Location
a. Biosphere Reserves			
Complejo Lagunar Ojo de Liebre	14 Jan. 1972	60,343	Baja California Sur
El Vizcaíno	30 Nov. 1988	2,493,091	Baja California Sur
Alto Golfo de California y Delta del Río Colorado	10 Jun. 1993	934,756	Baja California and Sonora
El Pinacate y Gran Desierto de Altar	10 Jun. 1993	714,557	Sonora
Sierra La Laguna	6 Jun. 1994	112,437	Baja California Sur
Archipiélago de Revillagigedo	6 Jun. 1994	636,685	Colima
Islas Marías	27 Nov. 2000	641,285	Nayarit
Isla San Pedro Mártir	13 Jun. 2002	30,165	Sonora
Isla Guadalupe	14 Apr. 2005	476,971	Baja California
Bahía de los Ángeles, Canales de Ballenas y Salsipuedes	5 Jun. 2007	387,957	Baja California
Marismas Nacionales	12 May 2010	133,854	Nayarit
b. National Parks			
Sierra de San Pedro Mártir	26 Apr. 1947	72,911	Baja California
Constitución de 1857	27 Apr. 1962	5,009	Baja California
Isla Isabel	8 Dec. 1980	194	Nayarit
Cabo Pulmo	6 Jun. 1995	7,111	Baja California Sur
Bahía de Loreto	19 Jul. 1996	206,581	Baja California Sur
Islas Marietas	25 Apr. 2005	1,383	Nayarit
Archipiélago de San Lorenzo	25 Apr. 2005	58,442	Baja California
Archipiélago de Espíritu Santo	10 May 2007	48,655	Baja California Sur
c. Wildlife Protection Areas			
Cabo San Lucas	29 Nov. 1973	3,996	Baja California Sur
Islas del Golfo de California	2 Aug. 1978	321,631	Gulf of California
Valle de los Cirios	02 Jun. 1980	2,521,776	Baja California
Sierra de Álamos-Río Cuchujaqui	19 Jul. 1996	92,890	Sonora
Meseta de Cacaxtla	27 Nov. 2000	50,862	Sinaloa
Balandra	30 Nov. 2012	2,513	Baja California Sur
d. Sanctuaries			
Ventilas Hidrotermales de la Cuenca de Guaymas y de la Dorsal del Pacífico Oriental	5 Jun. 2009	145,565	Pacific and Gulf deep trenches

FIGURE 3. Governmental officers and scientists from Mexico City visit Isla Rasa in 1963: Left, in a white shirt, Alejandro Villalobos from the Instituto de Biología of UNAM; second from right, with a dark felt hat, Dr. Enrique Beltrán (photographic copy taken by George Lindsay from an 8 mm film by Antero Díaz of Bahía de los Ángeles; courtesy of SDNHM archives).

the scientific support of George Lindsay and Daniel Anderson from the University of California, Davis, and the financial and conservationist support of Spencer Beebe from The Nature Conservancy, Enriqueta Velarde, at that time at UNAM, launched the first conservation project for the islands. The project produced, among many other applied results, the book *Islas del Golfo de California*, printed by UNAM and the Mexican Federal Government, which was extremely influential in bringing attention to the islands and their conservation problems.

Many of the biologists that participated in this early team are now crucial players in the conservation of the Gulf of California. The team included, among others, Alfredo Zavala, who played later a big role as Regional Director of the Wildlife Protection Area of the Islands of the Gulf of California; the late Jesús Ramírez Ruiz, who in the early 1990s eradicated introduced rodents from Isla Rasa; together with María Elena Martínez, Luis Bourillón, and Antonio Cantú, who are active conservationists in different NGOs in the region (see Bourillón *et al.* 1988). In many ways, it can be said that the conservation work at Isla Rasa was the catalyst that started most of the other conservation work in the Gulf of California.

Chronologically, however, Isla Tiburón was the first island of the Gulf of California to receive official status as a protected area, through a decree published a year before Isla Rasa's. The largest island of the Gulf of California, Tiburón, occupies

120,756 ha. In pre-Hispanic times Tiburón was an important part of the territory of the Seri Indians (or Comcaác, in their own language; Felger and Moser 1985). Because of this, the island is not only an important natural site, but also harbors important historic, archaeologic, and cultural elements of the tribe's history in the region. Although in the 20th century the Seri have not permanently lived on the island, they have always used it as their main fishing camp, hunting grounds, and plant collecting territory, and have always considered it part of their tribal land.

On March 15, 1963, Tiburón was decreed a Wildlife Refuge and Nature Reserve by President Adolfo López Mateos (DOF 1963). This first decree was issued as a result of an initiative by Enrique Beltrán. The ruling, however, was based on biological and ecological grounds, and failed to take into consideration the needs and demands of the Comcaác People. Twelve years later, in 1975, the Secretary of the Agrarian Reform gave the Seri formal possession of Tiburón Island as part of an *ejido* (*i.e.*, communal land) allotment for the tribe. This was the first recognition by the Federal Government of the Seri's right to their ancestral territory. On February 11, 1975, a decree was issued by President Luis Echeverría, restituting Tiburón Island to the Seri People as part of their communal property. Although this decree was basically issued as part of a series of governmental actions to empower native peoples within their traditional lands, it also had conservationist implications for the island as well as the mainland coast. The decree established that the coastal waters of the island could be only used by the Seri, and by their fishing cooperative, the Sociedad Cooperativa de la Producción Pesquera Seri (INE 1994), and declared it off-limits for other fishermen.

1.2. Biosphere Reserves and biological diversity

In the early 1970s, roughly at the time of Lindbergh's trip to Mexico City, many changes were occurring within the Mexican scientific and conservation groups. These scientific transformations also helped to protect the islands. In 1974 the Instituto de Ecología, A.C. (Institute of Ecology, a federally-funded non-profit research organization) started to promote the concept of Biosphere Reserves in the country. Although widely accepted at present, the idea of Biosphere Reserves, which had been developed by a group of ecologists in UNESCO's Man and the Biosphere Program (MAB), was radically new in 1975. Biosphere Reserves were conceived as natural protected areas where the indigenous populations living inside the area or in the surrounding "buffer zones" were encouraged to use their natural resources in a sustainable manner. The new approach departed radically from the concept of "natural parks" which basically advocated for pristine areas free of human influence. Rather, Biosphere Reserves promoted sustainable use as an effective tool for conservation, based on (a) the global approach to conserve biodiversity through a planetary network of protected areas; (b) the preservation of cultural diversity together with natural diversity; (c) the involvement of local populations in the protection of natural resources, and (d) the promotion of the sustainable use of nature.

The international success of the Mexican Biosphere Reserves caught the attention of Mexican environmental authorities, who realized that large natural areas could be protected under the new scheme as it did not preclude resource use but rather pursued a judicious utilization of natural resources. Although the islands of the Gulf of California were initially not conceived as a Biosphere Reserve but rather as a Wildlife Refuge (refugio de la vida silvestre), it was in the wake of these changes that the decree protecting them as a whole was issued in 1978 (DOF 1978).

2. PRESENT STATUS OF PROTECTED AREAS IN THE GULF OF CALIFORNIA

Mexico's environmental legislation, the Ley General de Equilibrio Ecológico y Protección al Ambiente (DOF 1988, 1996) recognizes eight categories of natural protected areas that can be established by the Federal Authority. These are: (1) Biosphere Reserves (reservas de la biosfera), (2) National Parks (parques nacionales, including both terrestrial and marine parks), (3) Natural Monuments (monumentos naturales), (4) Areas for the Protection of Natural Resources (áreas de protección de recursos naturales), (5) Wildlife Protection Areas (áreas de protección de flora y fauna), and (6) Natural Sanctuaries (santuarios).

The Mexican Federal Government has decreed ten Biosphere Reserves in the Gulf of California region, all operated under the administration of the National Commission for Natural Protected Areas (CONANP): (1) Complejo Lagunar Ojo de Liebre, (2) El Vizcaíno, (3) Alto Golfo de California y Delta del Río Colorado, (4) El Pinacate y Gran Desierto de Altar, (5) Sierra La Laguna, (6) Archipiélago de Revillagigedo, (7) Islas Marías, (8) Isla San Pedro Mártir, (9) Isla Guadalupe, (10) Bahía de los Ángeles, Canales de Ballenas y Salsipuedes, and (11) Marismas Nacionales (see Table 2).

The region also harbors eight National Parks (Sierra de San Pedro Mártir, Constitución de 1857, Isla Isabel, Cabo Pulmo, Bahía de Loreto, Islas Marietas, Archipiélago de San Lorenzo, and Archipiélago Espíritu Santo), as well as six Wildlife Protection Areas (Cabo San Lucas, Islas del Golfo de California, Valle de los Cirios, Sierra de Álamos-Río Cuchujaqui, Meseta De Cacaxtla, and the bay of Balandra), and one atural Sanctuary: the deep hydrothermal vents of the Guaymas Basin. Two very large and very important reserves—Valle de los Cirios and Islas del Golfo de

California—were originally decreed as Wildlife Refuges and were re-categorized in June 2000 into their current category as Áreas de Protección de Flora y Fauna (DOF 2000).

At present, UNESCO's Man and the Biosphere (MAB) Program has 42 Mexican reserves accepted into its international network of Biosphere Reserves, seven of which are in the Gulf of California region: (1) El Vizcaíno, in the central part of the Baja California Peninsula (admitted to the MAB network in 1993), (2) El Pinacate y Gran Desierto de Altar, in the core of the Sonoran Desert (1993), (3) Alto Golfo de California y Delta del Río Colorado, in the Upper Gulf of California (1995, also dedicated as a site of global significance within the International Convention of Wetlands or RAMSAR Convention), (4) Islas del Golfo de California (1995), (5) Sierra La Laguna, the high sierras of the Cape Region of Baja California (2003), (6) Islas Marietas (2008), on the southern border of the Gulf of California, and (7) Islas Marías, three islands in the Mexican Pacific immediately south of the Gulf (2010). Furthermore, the World Heritage Convention has accepted four areas in the Gulf of California region as World Heritage Sites. These are (a) the Whale Sanctuary of El Vizcaino and (b) the Rock Paintings of the Sierra de San Francisco, both in the Vizcaíno Biosphere Reserve and designated in 1993, (c) the islands and Protected Areas of the Gulf of California (2005), and El Pinacate and Gran Desierto de Altar Biosphere Reserve (2014).

As a Wildlife Protection Area, under Mexican Law the islands of the Gulf of California do not enjoy the same strict restrictions that are imposed on Biosphere Reserves. The reasons to designate the islands within Mexican legislation with a different category to the one they hold internationally is possibly related to the large size and the spatial complexity of the whole archipelago, and the difficulties involved in strict law enforcement within the whole protected area. In spite of their less-restrictive status under Mexican law, the islands of the Gulf of California are in practice managed as a large reserve and substantial efforts are devoted to their protection (Breceda *et al.* 1995, INE 1994). The relevance given by federal authorities to the islands of the Gulf of California is possibly the result of an effort to fulfil the Mexican Government's commitment with the UNESCO-MAB network and with the Global Environmental Facility (GEF), which has funded part of the conservation work on the islands. In 1996 the administration of the natural protected area was divided into three regional headquarters: (a) the southern islands are managed from an administrative office at La Paz, (b) Tiburón, San Esteban, San Pedro Nolasco, and some smaller islands near the Sonoran coast are managed from an office in Guaymas, and (c) the western midriff islands are managed from headquarters in Bahía de los Ángeles.

3. CASE STUDIES: MAIN CONSERVATION EFFORTS IN THE GULF OF CALIFORNIA

3.1. The Northern Gulf

3.1.1. The preservation of the Alto Golfo

From the mid-fifties it has become well known that the Upper Gulf of California (known in Spanish as the *Alto Golfo*) and the delta of the Colorado River are important sites for the reproduction and breeding of many species of birds and fish. This very productive region, however, has been under heavy fishing pressure. In 1975, the totoaba fish (*Totoaba macdonaldi*) was facing extinction through over-fishing. This problem forced the Federal Government to decree a moratorium for totoaba harvest in the Gulf of California.

Other problems, however, kept mounting. In the mid-eighties marine mammalogists started showing a strong concern on the population status of the vaquita porpoise (*Phocoena sinus*), which is endemic to the Upper Gulf of California. The vaquita is indeed a very rare marine mammal. Described in 1958, only a few specimens have been studied. The occurrence of vaquita specimens as incidental take in gill nets in the Upper Gulf started to signal an alert to Mexican and international conservation groups.

In the early nineties, the population of vaquita was estimated as less than five hundred. The vaquita was classified as endangered, and the International Whaling Commission labeled it as one of the highest priority marine mammals in the world. It was then that the Mexican Federal Government created, through the Secretary of Fisheries, the Technical Committee for the Protection of the Totoaba and the Vaquita (Comité Técnico para la Preservación de la Totoaba y la Vaquita), with the purpose of evaluating and studying the issue, and recommending adequate measures for the conservation of both endangered species. Dr. Bernardo Villa, one of the Mexican biologists who had dedicated much time to the studying of the fauna of the Gulf of California, was named President of the Committee, and it enjoyed the participation of several leading Mexican biologists and conservationists. Dr. Samuel Ocaña, formerly governor of Sonora and a devoted conservationist, was appointed technical secretary of the group. After a few sessions, it became evident that serious discrepancies existed between various constituents of the Committee. While some members favored immediate action to protect the Upper Gulf of California from the devastating effects of overfishing, others were of the opinion that regulating fisheries in any way would harm the local economy.

In June, 1992, an international meeting was organized in San Diego by the University of California Mexico-US Program (UC-MEXUS) to discuss two conservation issues of great relevance for marine mammals: the problem of dolphin incidental take in Mexican tuna fisheries, and the totoaba-vaquita extinction threat. The meeting was called by Dr. Arturo Gómez Pompa, a professor at UC Riverside, and also at that time special advisor on environmental matters to the President of Mexico. Thus, the problem of overfishing in the Gulf of California started to appear in the international arena, harming Mexico's reputation on conservation and natural resource management.

In 1992, a severe crisis struck the fishermen of El Golfo de Santa Clara and Puerto Peñasco, in Sonora, and San Felipe, in Baja California, all three located in the Upper Gulf of California. Their shrimp catches had fallen precipitously (Arvizu 1987), and the fishermen blamed the federal authorities in general, and the Secretary of Fisheries in particular, for failing to enforce fishing bans to allow the recovery of the resource. The idea started to grow among the fishermen that the sea had to rest and its fisheries had to recover.

In the summer of 1992, the Technical Committee met in Hermosillo, Sonora. At this meeting, both the Director General of Natural Resources (Dirección General de Aprovechamiento Ecológico de los Recursos Naturales) of Mexico's National Institute of Ecology, Exequiel Ezcurra, and Prof. Arturo Gómez Pompa, expressed their support for the idea of establishing a natural protected area in the Upper Gulf. Most members of the Committee showed sympathy for the proposal, but the representatives of both the Secretary of Fisheries (Secretaría de Pesca) and the National Institute of Fisheries (Instituto Nacional de la Pesca) expressed their complete opposition. As a result, it was decided to request to two of the most recognized research centers in Sonora, the Centro Ecológico de Sonora (CES) and the Centro de Investigación y Desarrollo de los Recursos Naturales de Sonora (CIDESON), to develop and elaborate upon a feasibility study for a Biosphere Reserve.

Towards the end of 1992, the study was completed. The next step was to gain the approval and the consensus of the fishing communities in El Golfo de Santa Clara, Puerto Peñasco, and San Felipe, as well as the *ejido* communities in the delta of the Colorado River itself. The first months of 1993 were employed in discussing with these communities the costs and benefits of a protected area. Slowly, the people in the area started first to accept and later to support the idea. In March, 1993, Sven Olof Lindblad, owner of Lindblad Expeditions, donated a week of usage time in his boat "Sea Bird" for conservation projects. In collaboration with the World Wildlife Fund, the National Institute of Ecology (Instituto Nacional de Ecología, or INE) from Mexico's Federal Government used the opportunity to assemble businessmen, scientists, conservationists, social leaders from the small-scale fisheries and traditional authorities from the indigenous peoples around the Gulf of California, and bring all these sectors together to discuss the issues around the sustainable management of the region. As a result of the "Sea Bird" cruise, a joint declaration was issued, signed by all the invited participants, urging the Federal Government to protect the habitat of the vaquita by declaring a marine reserve in the Upper Gulf. Finally, the project was presented to the Secretary of Social Development in the Federal Government, Luis Donaldo Colosio, a native of Northern Sonora and much interested in the idea. With the support of Colosio, the project moved forward.

In June 10, 1993, at a memorable occasion at Cerro Prieto, a volcanic mountain in the Gran Desierto near Puerto Peñasco, the President of Mexico, Carlos Salinas de Gortari, decreed the establishment of the Biosphere Reserve of the Upper Gulf of California and Delta of the Colorado River (Reserva de la Biosfera del Alto Golfo de California y Delta del Río Colorado, see DOF 1993). The project had strong support from both the local population and conservation groups. Important decision makers attended the ceremony, including many cabinet members from the Mexican Federal Government, the Governors of Sonora, Baja California, and Arizona, the US Secretary of the Interior Bruce Babbitt, and the traditional governor of the Tohono O'Odham (Papago) people, whose lands extend on both sides of the Mexico-US border.

The objectives of the establishment of this reserve were the conservation of endangered species both from the Gulf of California and the Colorado River estuary, including the vaquita, the totoaba, the desert pupfish (*Cyprinodon macularius*), and the Yuma clapper rail (*Rallus yumanensis longirostris*). The establishment of the reserve also intended to protect the reproduction and breeding of many other species in the zone. Perhaps more importantly, this was the first marine reserve established in Mexico. In spite of the opposition of the fisheries authorities, it opened the way for new marine protected areas in the Gulf of California, in the Mexican Pacific Ocean, and on the other coasts of Mexico. The debate around the Upper Gulf of California facilitated efforts by various conservation groups to extend the decreed protection into the waters adjacent to some important islands, opened the door for protecting the waters surrounding the islands in the Gulf of California, and set the pace for new marine protected areas to come, such as Bahía de Loreto, Cabo Pulmo Archipiélago de Revillagigedo, Islas Marías, Islas Marietas, Isla San Pedro Mártir, Isla Guadalupe, Bahía de los Ángeles, Canales de Ballenas y Salsipuedes, Archipiélago de San Lorenzo, and the deep vents of the Guaymas Basin.

Despite this positive legacy, the Upper Gulf Biosphere Reserve has continued to suffer from social conflict and natural resource degradation. Governmental authorities have tried to enforce different types of fishing gear, but the vaquita population is still in severe decline and the situation of the species is dire. Recently, the illegal fishing of totoaba has come back, driven by the high prices its swim bladder gets in the Asian food market. The recovery of the Upper Gulf marine ecosystem, the subject of conservationists' dreams when the reserve was created, still seems to be very far away. There are, however, some reasons for optimism: The Colorado River delta, which once supported lush vegetation and a rich biodiversity and had become became a salt-caked wasteland after the river was dammed, received in 2014 an experimental flood to help restore the ecosystem (Stokstad 2014). Through a partnership of NGOs (the Sonoran Institute, Pronatura Noroeste, and the Environmental Defense Fund), the Colorado River Delta Water Trust was created in Mexico to acquire and lease water to restore the delta.

3.2. The Midriff Islands

3.2.1. Isla Tiburón

Tiburón was the first island in the Gulf of California protected by presidential decree, closely followed by Rasa. The main purpose for protecting Tiburón in 1963 was to create a mule deer (*Odocoileus hemionus sheldoni*) refuge, protecting the species from the extensive poaching that prevailed in the Sonoran mainland (Quiñonez and Rodríguez 1979). The 1963 sanctuary was put under the management of the Secretaría de Agricultura y Recursos Hidráulicos (SARH, Secretariat of Agriculture and Water Resources) an agency of the Federal Government. SARH built basic facilities for poaching control, 130 km of dirt roads, two airstrips, a small wildlife research station, and some water reservoirs to improve habitat quality for game species. At that time, the hunting habits of Seri Indians were considered a threat to the game species and an essential part of the problem of game conservation on the island. As a result, no hunting permits were granted initially to the tribe, despite the fact that Tiburón had always been part of their traditional hunting territory.

Bighorn sheep (*Ovis canadensis mexicana*, the Sonoran Desert subspecies; see Monson 1980) were introduced in 1975 as a part of a federal program to study and protect bighorn in Sonora (Becerril-Nieva *et al.* 1988, cited in Hernández-Alvídrez and Campoy-Favela 1989). Twenty sheep (4 males) were introduced to the island, captured by staff from the New Mexico Department of Game and Fish in the mainland mountain ranges in front of the island (Montoya and Gates 1975). Before the sheep introduction, in 1967 two other species of mammals were introduced from the Sonoran mainland: 20 white-collared peccari (*Tayassu tajacu*) and 17 pronghorn antelopes (*Antilocapra americana*; Quiñónez and Rodríguez 1979).

In 1975, however, the government approach to Indian issues changed and the interests of the Seri people on the wildlife of Tiburón were taken into account for the first time. Under the administration of Mexican President Luis Echeverría, the island was returned to Seri ownership, although it still remained for a time under federal control. For two years (1975–1977) marines (the Mexican Navy had permanent presence on the island on small outposts since the 1970s) and game wardens prohibited Seri from landing on the island (Olivera and López 1988).

The bighorn sheep transplant was the only successful introduction. In fact, the population grew to a number between 500 and 600 animals, as evaluated through aerial censuses (Lee and López-Saavedra 1994, Pallares 1999, Wilder *et al.* 2014). In the late 1980s biologists from the Centro Ecológico de Sonora (CES, Ecological Center of Sonora, a state research center) continued the wildlife studies that SARH biologists initiated in the middle 1970s. Wildlife research on the island restarted with great vigor in 1995 when an ambitious project to study and manage bighorn sheep was launched. Scientists from the National University of Mexico, the Arizona Department of Game and Fish, and staff from two conservation NGOs, Unidos para la Conservación and Agrupación Sierra Madre, surveyed and studied the bighorn population. Under an innovative scheme for research and conservation funding, half of what is earned during the international auctioning of the sport hunting permits goes to support research by UNAM's scientists and for conservation and management actions for the bighorn sheep population on Tiburón. The other half goes to the Seri tribe. In 1998 the prices paid for the permits during an auction in Reno, Nevada raised to unprecedented levels: American hunters bid up to $395,000 dollars for two permits. The 1999 auction resulted in $150,000 dollars for two more permits (Navarro 1999).

The Seri community has been actively involved in this project, hiring a professional wildlife biologist for local field coordination and training a team of young Seri men as field technicians. Seris are also bringing to the project their traditional ecological knowledge about the wildlife of the island. The entire Seri community is expected to benefit from this sheep-hunting program. Money raised from hunting permits is deposited in a trust fund administered by a Seri technical committee. These monies are used for health, educational and cultural projects, as well as for supporting the operational cost of the Seri traditional government.

The bighorn sheep project in Tiburón also has the objective of providing animals to repopulate former bighorn sheep distribution ranges in Sonora, Chihuahua and Coahuila. Thus, with all this funding and support Tiburón Island is now contributing in an enormous way to the conservation of bighorn sheep in mainland Mexico, and at the same time it is generating another source of income for the Seri people. This innovative management project also plans to fund studies of other important species on the island, like the endemic mule deer, apparently suffering from habitat competition by the sheep, and predation from the growing coyote (*Canis latrans*) population. Under a new federal Program for Wildlife Conservation and Diversified Productive Use of Land, Tiburón Island is now managed as a Unit for the Management and Sustainable Use of Wildlife (UMA for its acronym in Spanish).

An interesting sequel to the bighorn story occurred in 2014. Despite the success of the bighorn introduction, this conservation story has been controversial due to the non-native status of bighorn sheep on the island. The impact of unchecked bighorn sheep herbivory on the island's flora, which includes several regional endemic species, was not considered prior to the introduction. However, in 2012 during a field survey for fossil woodrat (*Neotoma*) middens on Tiburón Island, Ben Wilder we discovered large pieces of an apparent sheep dung in a small rock shelter in the eastern foothills of Tiburón. Pellets from the recovered dung mat were ^{14}C-dated to 1476–1632 calendar years before present, proving that bighorn sheep had been in the island at least since the end of the Pleistocene to around 1000 years before present (Wilder *et al.* 2014). The bighorn "introduction" had really been a case of rewilding the island with its native fauna.

3.2.2. Isla Rasa

Rasa island, the major site for breeding seabirds in the Gulf of California (Bancroft 1927, Case and Cody 1983), has served as a role model for successful ecological conservation of islands in the Gulf of California. Immediately after its legal protection in 1964 (DOF 1964) the seabirds on this island were studied intensively, and protected thereafter thanks to an enormous commitment of effort by almost three generations of Mexican biologists, and the support from numerous research and conservation organizations (Tobías 1968, Velázquez-Noguerón 1969, Velarde *et al.* 1994, Velarde 1988, 1993).

In the early 1960s a concern for the protection of Rasa grew following drastic reductions in the population numbers of nesting seabirds caused by egg collecting. In 1940, the population of seabirds (all species combined) was estimated to be one million (Walker 1965), in the late 1960s it had reduced to 25,000 (Barreto 1973), and possibly reached a historic low with an estimated number of 5,000 in 1973 (Villa 1983). The pioneering conservation efforts and lobbying of Louis Wayne Walker of the Arizona Sonora Desert Museum and the National Audubon Society, George Lindsay and Robert Orr of the California Academy of Sciences, Bernardo Villa from the National University of México, and some leading residents of Bahía de los Ángeles, notably Antero Díaz (Velarde *et al.* 1985), led the federal government to declare the island a seabird sanctuary.

Once the island was declared a sanctuary, biologists working for the Mexican Direction of Wildlife spent time on the island during the seabirds' breeding season

FIGURE 4. Enriqueta Velarde disentangling an elegant tern (*Thalasseus elegans*) from a mist net for biometric recording in Isla Rasa, *ca.* 1988 (photo: Fulvio Eccardi).

to provide on-the-ground protection, and to collect baseline data on population numbers. In 1965 a two-room stone house was built on the island (Vidal 1967). The lengths of stay of researchers on the island became more prolonged every year, as UNAM students working under Villa's guidance became involved in the conservation efforts. Villa himself spent many seasons on the island between 1975–1985, and in 1979 one of his students, Enriqueta Velarde, took over the research and conservation tasks inspired by Villa's remarkable pioneering work (see Figure 4). Under Velarde's direction, biologists have been present during the seabird breeding season (middle March to early July) from 1979 to the present time. These scientists and students have researched in detail the seabirds' breeding ecology and behavior, and the island's natural history. They also have helped prevent possible disturbance by the 300 or more ecotourists that visit the island every year (Villa *et al.* 1979, 1980, Velarde and Anderson 1994), and deter fishermen from collecting eggs, and landing or hiking in the nesting areas. The success of this island research and protection is evident. Seabird populations have rebounded dramatically: Heermann's Gulls maintained an estimated average of 260-350 thousand birds throughout the 1990s (Vermeer *et al.* 1993; Velarde and Ezcurra, this publication), while the Elegant Terns increased from 45 thousand individuals in the early 1990s to around 200 thousand birds in 1999 (Velarde and Anderson 1994; Velarde *et al.*, in this publication). Regardless of numerous obstacles, since 1979, the seabird population numbers and annual breeding success have been monitored systematically by a dedicated band of researchers and graduate students.

In 1993–1994, a program to eradicate introduced rats (*Rattus rattus*) and mice (*Mus musculus*) was initiated by the late Jesús Ramírez, who also did the pioneering research to start the Bighorn Sheep program in Tiburón Island. The complete eradication of introduced rodents using modern rodenticides was achieved by 1995. Researchers have since found no sign of rodent activity in the island while doing monitoring work. Now that the island is free of introduced mammals, scientists are monitoring ecological changes in the nesting colonies, the vegetation, the insect populations, and have plans to restore the populations of burrow-nesting seabirds that may have once used this island (such as the Craveri's Murrelet *Synthliboramphus craveri*, the Black Storm-Petrel *Oceanodroma melania* and Least Storm-Petrel *O. microsoma*, and perhaps even the Black-vented Shearwater *Puffinus opisthomelas* that was present in the island in the early 1920s (Bancroft 1927, Boswall and Barrett 1978). Perhaps more importantly, the continued presence and the relentless work of Enriqueta Velarde on the island has yielded one of the most detailed datasets in the world on nesting seabirds and their interaction with pelagic fish, and has produced a long trail of research papers describing the dynamics of the Midriff marine ecosystem (Velarde *et al.* 2004, 2013, Vieyra *et al.* 2008).

3.2.3. Bahía de los Ángeles

The concern for the protection of the islands inside the Bahía de los Ángeles was fueled by members of the local Ejido Tierra y Libertad, especially the late Antero Díaz and his family, and in collaboration with several American researchers working in this area since the late 1950s. In the early 1970s the oceanographer Antonio Reséndiz arrived at Bahía de los Ángeles to start a small program devoted to sea turtle research, with the help of Dr. Grant Bartlett of the Laboratory of Comparative Biochemistry in San Diego. Reséndiz' work was not limited to sea turtles, as he collaborated extensively with almost all researchers that arrived at Bahía de los Ángeles, and founded Campo Archelon, a small research center. With the support of his wife Betty since 1985, the center developed into a focal point for local conservation efforts in the bay area. He is the current President of the Ejido Tierra y Libertad.

In 1988, efforts by residents led by Carolina Espinoza culminated in the construction of the local Museum of Natural History and Culture. This exceptional museum has functioned as an information center for visitors describing the natural and cultural history of the area, highlighting the ecological importance of the islands, and providing environmental education opportunities for the local people.

The proximity of Bahía de los Ángeles to southern California, and its small islands inside protected waters, make this area an ideal place for natural history trips and ecotourism. The growth in human use and the impacts on the bay and its islands prompted a binational group of researchers, governmental resource managers, and key local people to draft a management plan for the islands (Bourillón and Tershy 1997). A prioritized set of actions was proposed, which involved placing information signs on the common landing and camping sites on the islands, defining and delimiting hiking trails, and starting an information/orientation/registration system for island visitors. With financial support from a U.S. Fish and Wildlife Service grant under a joint program with Mexico's National Institute of Ecology, and with the support of Dr. Dan Anderson and the late Dr. Gary Polis, a group of members of the *ejido* established a committee in 1998 to fully implement the plan (Jiménez *et al.* 1999). This management plan has shown how the active participation and involvement of a local community can effectively increase local conservation through simple and low cost management actions, usually not adequately considered in large-scale programs for island conservation.

The growing awareness of the importance of environmental conservation by the community of Bahía de los Ángeles eventually yielded larger fruits. Thanks to the joint work of the community and Pronatura Noroeste—a conservation NGO—in June 2007 the larger coastal area around Bahía de los Ángeles was decreed as a Biosphere Reserve by the Mexican Federal Government. Together with the decree, a comprehensive study was published establishing the baseline conditions of the region and setting a precedent of ensuring sound scientific information accompanying the declaration of new Natural Protected Areas (Danemann and Ezcurra 2008).

3.3. The Lower Gulf

3.3.1. Conservation in the Bay of Loreto

Loreto is a small town on the Central Gulf Coast of Baja California Sur, its bay is protected by five islands (Coronado, del Carmen, Danzante, Monserrat and Santa Catalina). The growing pressures of large, industrial fishing boats (mainly shrimp bottom trawlers) on the fisheries of the bay induced a collapse of the local fisheries in the 1970s and 1980s, and in doing so generated a concern among the local small-scale, or *panga*, fishermen and the sport fishing operators as to how to protect the bay from overfishing.

Many measures were proposed, some extreme ones including the sinking of boats into the bay to destroy the shrimpboat dragnets, but little was done at first. In 1995 the Municipal President of Loreto, Sr. Alfredo García Green, started meeting with conservationists and concerned citizens to discuss the issue. Under the leadership of Grupo Ecologista Antares (GEA, a local conservation group), a proposal was prepared and submitted to the Federal Government to protect the Bay of Loreto, including its five islands. On July 19, 1996, the Parque Marino Nacional Bahía de Loreto was created by a Federal decree (DOF 1996a). In December 1996, when Mexico's Environmental Law was changed, the marine park was re-categorized as a National Park (DOF 1996b).

Conceptually, this 206,580 ha National Park was major breakthrough. Although the islands of the Gulf of California had legal protection since 1978, the sea surrounding them did not. Many conservationists have argued that the decree protecting the islands should be extended to the marine ecosystems around them, but fierce opposition from the large-scale fisheries lobby had prevented this from happening. In the Bay of Loreto, the concerns of the local community proved to be stronger than the short-term economic interests of the fishing industry. In 1999, the park had financing for a Director, vehicles, basic equipment, and an office. It also had a working management plan and the full support of the local people, two facts that promote the park as a leading coastal protected area in Mexico.

3.3.2. Isla Coronado

In 1995, two Italian investors proposed building a hotel on Isla Coronado, a small, 850 ha island situated 11 km north of the town of Loreto. This island being part of the Protected Area of the Islands of the Gulf of California, the project required an Environmental Impact Statement (EIS). The hotel of 40 rooms was designed to have all the technological advances to be "environmentally friendly": solar panels for water heating, sewage treatment, water desalinating plant, and careful management of solid waste. The project was presented by the proponents as a viable alternative for the protection of the island. It planned to concentrate on low impact tourism and to enable a research station to be built next to the hotel that would monitor the island's wildlife and provide guidelines for a conservationist management of the site (Anonymous 1995a). The project, however, was strongly challenged by local and national conservation and citizen groups, and was finally abandoned.

Nevertheless, the development of the proposal, the discussion that arose around the project, and the arguments for its final cancellation, offer another example of the strong attraction islands exert for tourist resorts, and of the rationale used to justify their development. The Coronado project is also a prime example of the problems, conflicts of interest, and dangers for island conservation that can be caused by lack of clear governmental policies.

The main argument used by the developers was the limited conservation and management actions that were in place on Isla Coronado despite its legal protection since 1978. The presence of introduced animals (cats and sheep) and the high levels of human use by fishermen and tourists were used as strong arguments to propose that a research station, to be sponsored by the hotel and managed by the University of Baja California Sur (Universidad Autónoma de Baja California Sur, or UABCS), was the only and best option to protect the island and ameliorate its deteriorated ecological status. The probable, but not yet certain, extinction of the endemic pack rat of Coronado (*Neotoma bunkeri*) due to 30 years of cat predation was another argument used to support the claim that the island was disturbed and could be developed.

However, most of the opponents to the project argued that once the place is connected to the coast by means of daily transport of food, personnel, tourists, baggage, people, machinery, trash, etc., it would be almost impossible to ensure that no new exotic animals or weedy plants will reach the island. Coronado Island is now part of the Parque Nacional Bahía de Loreto and it is better protected than it was before. Additionally, the introduced species are being successfully eradicated (Arnaud 1998).

There are ongoing development plans and growing pressures to develop other Gulf islands for tourism, mainly those in which private persons can claim ownership, such as San José, Cerralvo, Carmen, and Espíritu Santo. The same arguments brandished for Coronado, namely that protection of the island was not being enforced and that an "environmentally minded" development could protect the island better, are being used to pursue other development proposals in the Gulf of California.

3.3.3. Isla del Carmen

Possibly the most beautiful and scenic of the islands of the Bay of Loreto, Isla del Carmen—an island with private ownership claims—has been for many years a favorite destination for ecological tourists, and plays a major role both in the Protected Area of the Islands of the Gulf of California in general, and in the Loreto Bay National Park in particular.

Based on the apparent success of the breeding program of the Sonoran Bighorn sheep in Isla Tiburón, the National Institute of Ecology of Mexico decided to promote a similar program in Isla del Carmen, this time aimed at the Baja California subspecies (*Ovis canadensis weemsi*), an endemic taxon that is found only in the Sierras El Mechudo, La Giganta, and Las Tres Vírgenes within the Peninsula of Baja California. In 1995, the Mexican company Salinas del Pacífico, S.A., presented a project to recover the peninsular populations of bighorn by breeding them in the protected environment of Isla del Carmen (Anonymous 1995b). The National Institute of Ecology supported the plan, and gave the company a permit to capture 15 adult bighorn, 12 females and 3 males, in the Sierra de El Mechudo. The master plan establishes that when the herd reaches 175 individuals in an estimated time of

10 years, adults will be captured and used to repopulate the peninsular mainland. The plan, however, was received with criticism by conservationists in the Peninsula. Firstly, the peninsular population was evaluated in the early 1980s, and the count gave some 5–7 thousand individuals, a large number by any count. Secondly, there is no evidence that the mainland population is under any important threat. Thirdly, an island population size of less than 175 does not seem sufficiently large to insure the recovery of a peninsular population of many thousand. And, lastly, although the Baja California bighorn is indeed a rare and valuable wildlife species, trying to insure its long-term survival through a program that is based on the introduction of these game animals into fragile island environments is not justifiable. In short, although the bighorn program in Isla del Carmen was done with a conservationist justification, there is reason to doubt the value of the enterprise from a truly conservationist perspective.

3.3.4. Isla Espíritu Santo

Espíritu Santo is a large, 10,200 ha island surrounded by a set of smaller islets known as Isla Partida, Los Islotes, La Ballena, El Gallo, and La Gallina. It lies some 20 km north of the city of La Paz. Because of its proximity to La Paz, the island has been intensely used in the past and is still the most intensely visited island of the Gulf of California. It is filled with evidence of pre-hispanic occupancy by the Pericú people. In the 19th century Don Gastón Vives established here the first pearl oyster farm in the world. The ruins of the pearl farm ponds are still visible in Bahía San Gabriel, south of the island.

In the 1960s the ports in the state of Baja California Sur were granted legal status as duty free areas, and the economy made a rapid transition from ranching and agriculture into international commerce. As a result, communications developed rapidly: ferry ports, airports and the transpeninsular highway were built, and tourism started to take off. Some pioneering entrepreneurs who loved the natural beauty of the region started to develop at that time a new brand of nature tourism that involved low-impact activities such as whale watching, kayaking, camping, and visits to the islands. Eco-tourism was then a new and revolutionary concept in Mexico, and its development in the Gulf of California has since set an example for other regions of the country. Espíritu Santo became a major destination for local nature tours. Coastal fishing in open *panga* boats also developed in the 1960–1970s, and the fishermen started to use the island for temporary camps, and were still using it for that purpose in the 1990s. Twenty-two camps were in operation in Espíritu Santo in 1999. Finally, the academic and research sector also developed with the new economy in Baja California Sur. The University of Baja California Sur and two top Mexican research centers were established in La Paz in the 1970s, and researchers started to visit the island and use it as a convenient research area and field station. In spite of these uses, the island is still in an extremely good state of conservation, an empirical fact that shows that low-impact nature tourism can indeed meet its declared goals.

Despite the common use by many stakeholders, the island had legal owners. In 1976, two years before the decree protecting the islands of the Gulf of California was issued, the Secretaría de la Reforma Agraria (SRA, or Secretariat of Agrarian Reform) gave legal tenure of the island to the Ejido Alfredo Bonfil from La Paz. In the 1990s, facing a crisis of underground water depletion in the mainland, the *ejido* started to look for alternative, non agricultural uses for their land and turned to Espíritu Santo. In 1992 the Mexican Constitution was amended to allow communal *ejido* lands to be privatized, and the Ejido Bonfil obtained authorization from SRA to parcel out 90 ha of island acreage for development. Thus, a frontal conflict arose between the presidential decree declaring the islands of the Gulf of California a natural protected area, and the development authorization for Espíritu Santo. This lead in turn to a sort of legal stalemate in which the *ejido* people had the right to develop the island but had not been able to get the permits from the Secretariat of the Environment (Mexico's Secretaría de Medio Ambiente, Recursos Naturales y Pesca, or SEMARNAP).

In order to resolve this situation, the *ejido* decided to cooperate in the preparation of a management plan for the island. They rapidly realized that their biggest chance of obtaining some income from the island's land surface lay in being able to use it in a manner compatible with its status as a natural protected area. The management plan was drawn up by CICIMAR, a local research center, with the participation of the Management Authorities of the protected area Islas del Golfo de California, ISLA (a conservation NGO), The Nature Conservancy, the University of Baja California Sur, the Mexican Center of Environmental Law (Centro Mexicano de Derecho Ambiental, or CEMDA), and, most importantly, the Ejido Bonfil. A number of workshops were held, and in 1998 the final document was ready. The management plan for Espíritu Santo was the first island-specific plan to be finished in the Gulf of California, and it has become a landmark for regional conservation. The fact that the *ejido* landowners agreed to participate—and in doing so accepted the potential consequence of there being restrictions to development in their own insular lands—was indeed a turning point and a lesson for the growing pressures for traditional tourism development that the islands of the Gulf of California are facing.

The successful work with the Ejido Bonfil brought together an alliance of Mexican and international conservation organizations and a diverse group of funders to ensure that the island remained as protected area. Mexican grant makers such as the Mexican Foundation for Environmental Education (FUNDEA) and Fondo Mexicano para la Conservación de la Naturaleza, and International funders such as the Marisla Foundation and The David & Lucille Packard Foundation, got together with Mexican conservation NGOs (ISLA, Niparajá, Pronatura, and CEMDA) and two international NGOs [World Wildlife Fund (WWF), and The Nature Conservancy (TNC)] to bring Espíritu Santo under the control of the Mexican National Commission for Protected natural Areas (CONANP). The legal tool used was that of a "negotiated expropriation" in which the Ejido Bonfil voluntarily accepted having their land expropriated at a previously agreed price; the funders and the NGOs raised the funds necessary to pay the ejido; while in the same action the Federal Government expropriated the land to give it to CONANP.

The general assembly of the ejido members voted the initiative in June 2001 and agreed to the cession of the island for the negotiated prize. Another year would pass during which 36 private plots that had already been sold by the ejido were bought back, stipulating that the land was being bought to be donated to the nation of Mexico as part of its system of protected natural areas. In January 2003 the expropriation decree was finally issued, and on February 25, 2003, President Fox took part in a public ceremony in La Paz to formalize this historic expropriation with the local State authorities, the ejido members, and local conservation groups. Four years later, on May 10, 2007, a decree was issued by President Felipe Calderón declaring the waters surrounding Isla Espíritu Santo as a National Park (DOF 2007), adding the adjacent marine environment to the land surface of the island that was already under protection. Despite the proximity to La Paz and the pressures for development it once had, the island is now legally safe, and is, to this day, one of the most successful marine and insular protected areas in the Gulf of California.

3.3.5. Cabo Pulmo

The Castro family came in the early 1930s to the bay of Cabo Pulmo to fish for pearl oysters after they became scarce in the Bay of La Paz. Enrique Castro, the founder of the community, free-dove for pearl oysters on the reefs around Cabo Pulmo. The work was hard and perilous (see Figure 5). The mother of pearl and the pearls they collected were sold at a meager price to merchants traveling up and down the coast on horseback. In their 1939 exploration book *The Log from the Sea of Cortez*, John Steinbeck and Ed Ricketts described in detail the ecological richness of the reef, but also highlighted the poverty of the community and the unending decline of the pearl fishery. Towards the end of the 1930s the pearl oysters were running out and the community was turning more and more to fishing (Squires 1959).

FIGURE 5. A typical pearl fishing skiff from Baja California Sur, *ca.* 1930 (courtesy of the Archivo Histórico de Baja California Sur).

At first the family concentrated on catching sharks, which are large and easy to catch with a bait line. When dried, they were sold as salt cod. Within a few years when the sharks ran out they turned to green turtles, which at the time were very abundant in the Gulf. Before long the turtles became rare, too, and so they turned to finfish. As the finfish declined at Cabo Pulmo, the men had to travel further and further out to sea and up and down the coast to feed their families.

To survive the community family began to travel to Bahía Magdalena in the Pacific coast to fish during the summer for spiny lobster and, if they could find any, for abalone. They would then return to Cabo Pulmo in the winter. But competition for lobster was fierce, and their catch provided barely enough for a meager subsistence. Mario Castro, grandson of Enrique, decided to confront their increasingly paltry condition and traveled in the early 1970s to Cabo San Lucas in search of employment. Here he discovered that tourists would come to the Cape to dive and explore. Mario, who was a good free-diver like his father and his grandfather, was offered the opportunity to become a dive instructor. Before long, he returned to

Cabo Pulmo as a newly qualified diving instructor with a plan to earn a living taking divers out onto the beautiful reefs of Cabo Pulmo he knew so well.

By the late 1980s there were very few fish on the reef, and visiting scientists from La Paz and around the world started talking to the community about protecting the reef and the remnants of their once-plentiful living resources. The community gathered to discuss the way forward and decided that, if they were going to succeed in the new business of diving they needed to create a marine park. With the help of local conservationists, in 1992 the community of Cabo Pulmo petitioned Luis Donaldo Colosio, Minister for the Environment, to declare their coast a marine park and a protected natural area. Within three years, in 1995, a region of 71 km^2 was decreed as Cabo Pulmo National Park. At that time, the reefs at Cabo Pulmo were notable only for their coral formations as, in all other respects, the depleted populations of large fish resembled those of any other rocky reef in the region.

A Mexican scientist, Octavio Aburto, undertook a survey of more than 150 reefs in the Gulf of California, including Cabo Pulmo, in 1999. Four years after the Cabo Pulmo National Park had been created, the reef was still badly degraded. In 2009, Aburto again undertook a repeat survey of all the Gulf of California reefs he had documented ten years before. All but one reef appeared to be either in the same poor condition or had further deteriorated. The exception was Cabo Pulmo, where the biomass had increased by almost 500% and the biodiversity had doubled (Aburto-Oropeza *et al.* 2011). The Cabo Pulmo community had zealously protected their home reefs in their National Park, which had now become an outstanding example of what reefs once looked like before exploitation. They had reverted to the wild; they had transformed a broken marine ecosystem into a flourishing and vibrant one that people from all over the world were attracted to, and they had gone from depending upon extracting living resources for the local markets to making a livelihood by keeping those same resources alive.

But this apparently happy ending was shadowed by new threats. The pulmeños—the members of the Cabo Pulmo community—were recently been engulfed in one of Mexico's most outstanding conservation discussions. A Spanish developer applied for a federal permit to initiate a mega-development project at the margins of the marine park. The project, first called Cabo Cortés, proposed the construction of 15 large hotels, thousands of villas and holiday houses, a large marina, and two golf courses side by side with the marine park and the small Cabo Pulmo community. The project would have demanded some 9 million cubic meters of water annually (plus some 15 million as a by-product of the settlement of services for this gigantic development) from a strategic aquifer that has already reached its full capacity. Worse still, the nitrogen fertilizers leached from the site, the increased load of sediments, and the eutrophic wastewater dumped into the sea would have meant, in all certainty, the decay and eventual death of the Cabo Pulmo reef.

The community acted. All the pulmeños became organized, they teamed with Mexican and international conservation agencies, they built alliances with marine scientists studying their reef, and learned to communicate with the media using the internet and social networks. Patiently, but with incredible constancy, they built their case. They convinced the Mexican society they were not against progress, development, or change—in fact, they had been harbingers of social innovation—but were opposed to environmentally destructive development. The discussion raged for two years, with more and more organizations taking sides with the unlikely champions, the pulmeños. Actors, intellectuals, scientists, all joined in.

Eventually, the community's perspective won: On the morning of June 15, 2012, the President of Mexico, Felipe Calderón, publicly announced the cancelation of the Cabo Cortés project, arguing that it had failed to demonstrate its long-term sustainability and the lack of significant impacts on the Pulmo reef, Mexico's most noteworthy success story in marine conservation.

After its cancellation, two further projects by two different development companies with a similar proposal, have attempted to build large developments in exactly the same site. The very success of the community in the conservation of their reef makes the place attractive for environmentally-disruptive developments. In these two occasions, however, the community was well prepared. Using the social networks, a response was quickly organized. Scientists read the new Environmental Impact Statements and found strong elements of criticism. The new studies failed in meeting the standards the Mexican legislation requires, and some of its information had been fabricated, or falsified. With the help of some Mexican non-profits and the Council for Protected Areas, the scientists demanded legal action against the developers. The first project—Los Pericúes—was cancelled on August 31, 2012, by the company itself who realized the project was not going to be authorized. The second project—Cabo Dorado—was denied by the environmental authority on May 30, 2014, for failing to meet required sustainability standards.

In many ways, the members of the Cabo Pulmo community have become local heroes and for the first time in history the country is looking at marine conservation with interest. The success story of Cabo Pulmo is viewed by many as one of those rare stories in which a small group of persons with a well-defined dream are able to prevail against all odds. The story of Cabo Pulmo has shown how marine protected areas can indeed offer an alternative to heal overfished seas, turning degraded coasts into a new vision of prosperity for all. The return of the large fishes to Cabo Pulmo is also the return of a dream to Mexico's coasts.

4. CONCLUDING REMARKS

A radical change has occurred during the 1990s in the management of some protected areas in Mexico, including the islands of the Gulf of California. During President Zedillo's administration (1994–2000), the National Commission for Protected Natural Areas was created. Following the excitement of the Rio Summit in 1992, Mexico started negotiations with the Global Environmental Fund to procure international funds for its protected natural areas. In addition, the Mexican government itself committed to invest a growing part of its budget towards conservation. From "paper parks" with no fixed budget, the protected areas in the Gulf of California region now have a modest but permanent financial flow that supports their operations. As part of the negotiations with GEF, the Mexican Federal Government agreed to permanently support the salary of the basic managerial staff. This commitment, taken in the mid-1990s, has been not only maintained but expanded. In the case of the islands of the Gulf of California, and because of the sheer size of the protected area, three administrative offices were established in 1996, operating out of (a) La Paz, Baja California Sur, (b) Guaymas, Sonora, and (c) Bahía de los Ángeles, Baja California. A fourth office was established in Loreto, Baja California Sur, to supervise the Loreto Bay National Park. Thanks to these actions, the local inhabitants of all the islands of the Gulf of California—temporary residents totaling some 700 or less at any given time—and of those of the surrounding communities are in many parts slowly changing their economic activity from traditional fishing to the services sector, including tourism services, field research, and education. The general management plan of the protected area Islas del Golfo de California, finally approved in October 2000, aims to promote carefully channeled ecotourism, with emphasis on environmental education.

Conservation in the Gulf of California region has progressed through the support of researchers, non-governmental organizations, local communities, and local, state and federal governments. The involvement of local groups as allies in conservation has possibly been the single most important element in island conservation. Local commitment has been the driving force of environmental protection in the islands and the key to the success of conservation programs.

Most of the attempts to develop the islands and other pristine natural areas have been based on the argument that some of there is already a certain level of environmental degradation, mostly as a result of introduced species and of exploitation of natural resources. However, development of these areas, and in particular of the Gulf islands, would only generate more degradation. It is entirely false that by developing one or a few well preserved natural areas the rest may be better conserved. Empirical experience in other regions of Baja California such as Los Cabos and Nopoló has shown that once development programs are established, others soon follow. No island is dispensable, and that all must be protected effectively. If some of the islands are degraded, then the conclusion must be that the island should be restored, not that it should be developed. The experience of eradication of introduced fauna in Isla Rasa—and the subsequent recovery of the marine bird populations—shows that restoration ecology can be very effective in these environments. No island in the Gulf of California is unimportant for conservation.

Finally, the incorporation of the Gulf of California islands and regional protected areas into MAB's international network of Biosphere Reserves and into the World Heritage List generates an immense responsibility for the Mexican Government and the local communities. The islands are now a recognized part of the global heritage of the world's biological diversity, and efforts must be done to protect them effectively as such.

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NEOGENE SEDIMENTARY RECORD OF THE GULF OF CALIFORNIA: TOWARDS A HIGHLY BIODIVERSE SCENARIO

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The biodiversity in Baja California and the Gulf of California is the result of biological processes related and influenced by the geological history of the region. Particularly important is the opening of the Gulf, since it represents the onset of one of the most diverse marine basins and an effective barrier to continental dispersion. Geologic models propose opening of the Gulf of California during Miocene times. Marine fossils indicate that at approximately 12 Ma, a marine basin formed in the northern part of the Gulf, and by 8 Ma, reached from southern California to Santa Rosalía in the south, forming two biotas, one in Sonora and another one in Baja California. This proto-Gulf could have been connected to the Pacific somewhere south of the Sierra San Pedro Mártir, while the southern part of the Peninsula was still connected to the continent. Then, from 6 to 3 Ma, a sea transgression connected all the depressions, reaching the modern configuration with the Peninsula completely separated from the continent. After this interval, opening of other seaways took place, one at 3 Ma, which isolated Los Cabos region, and another one at ~1-1.6 Ma, near central Baja, which separated the biotas into two groups.

1. INTRODUCTION

The great biodiversity of the region around the Gulf of California (hereafter referred to as the Gulf) is due to the diverse ecosystems in and around the region. These range from continental Sonoran Desert with terrestrial Neotropical and Neartic taxa, to marine fauna with Californian, Panamic, Caribbean, and even tropical West Pacific affinities. At the present time, the Baja California Peninsula (hereafter referred to as the Peninsula) constitutes an enormous barrier that separates the tropical-subtropical

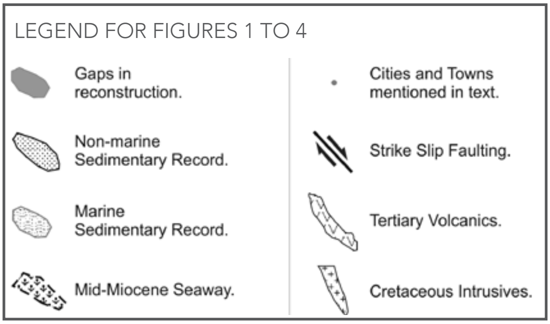

FIGURE 1. Location map of main regional features and points of interest.

marine organisms inhabiting the Gulf from the temperate ones in the Pacific Ocean at the same latitude. Conversely, the Gulf acts as an effective barrier which, together with the Sonoran arid region, precludes mixing of most terrestrial organisms living in mainland Mexico and in the Peninsula (see Figure 1).

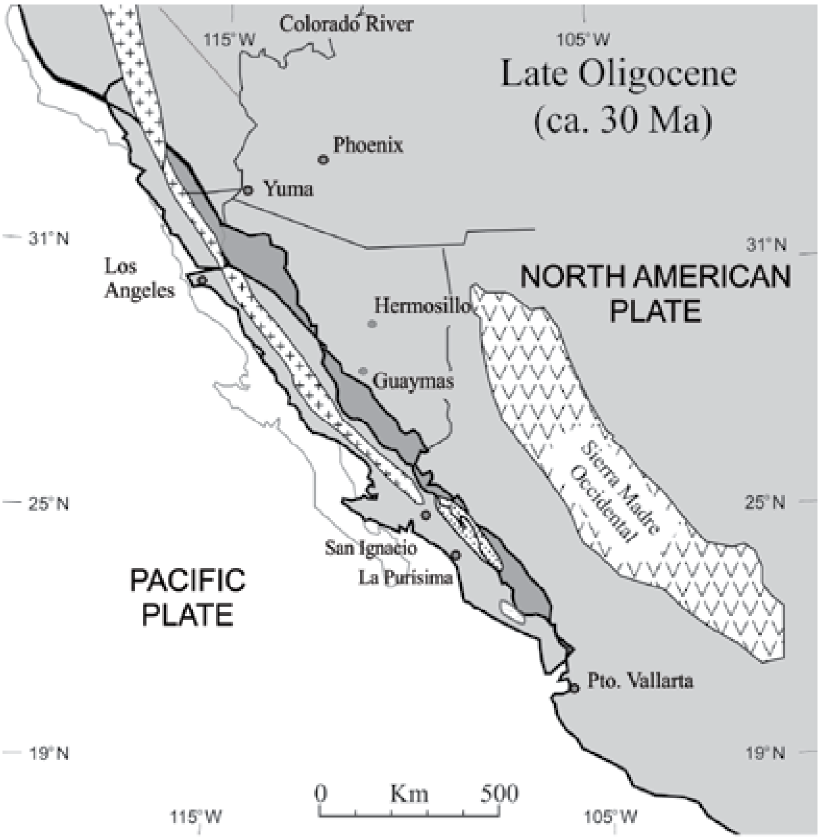

FIGURE 2. Location of the Baja California Peninsula next to mainland Mexico, during Oligocene times (30 Ma). Palinspastic reconstructions of figures 2 to 4 are based on models presented by Lonsdale (1991), Bohannon and Parsons (1995) and Helenes and Carreño (1999).

The Gulf and the surrounding coasts are the result of many geological events that determined the evolution and distribution of the organisms inhabiting the region. The complex geological history of this region allowed the formation of passages and barriers that enhanced or barred the dispersion of organisms at different times. According to our current knowledge of the geological characteristics of the Gulf, the separation of the Baja California Peninsula and the Gulf of California and therefore the configuration of the actual scenario took no less than 25 million years (see Figure 2).

It is difficult to establish with confidence the precise geological moment in which a marine or terrestrial basin begins to form, as well as its extent, structure and shape through time. It is also complicated to determine the exact timing and intensity of the geological processes involved in the formation or disappearance of these basins. However, we can establish that in the Baja California region, from at least 90 Ma (Late Cretaceous) to approximately 37 Ma (late Eocene), the geologic framework was characterized mainly by a subduction (compressive) tectonic regime. This was caused by the subduction of the oceanic Farallon plate under the western margin of the continental North America plate (Atwater 1970, 1989). Sometime in the late Eocene, the Pacific-Farallon spreading ridge collided against the continent and caused several important changes in the adjoining areas. These changes can be related to three critical stages that permit to explain the evolution of a marine basin such as the Gulf. After the first contact of the Pacific plate with North America, the initial changes in the area, are related to signs of continental crust extension at ~27 Ma, when the normal faulting, characteristic of the Basin and Range extension, reached the eastern side of the actual Gulf (Gans 1997). In this stage, is noticeable a change in the style and composition of the volcanism, from subduction related to one caused by continental extension, at ~14 Ma. Also during this stage, the continental crust became thin enough to subside below sea level, developing the earliest marine basins in the region, over thinned continental crust at ~12 Ma (Helenes *et al.* 2009). Next, in an intermediate stage, there was a change from mainly normal faulting to strike-slip at ~6 Ma, which caused a great part of the displacement of Baja California (Oskin *et al.* 2001). And finally, the stage when new oceanic crust begins forming under the basin at ~3 Ma, in the southern part of the Gulf (Lonsdale 1991).

The initial stages of the regional geologic evolution are clearly described elsewhere in this volume (Martín-Barajas, this chapter). In this paper, we describe the geological and sedimentary record of the Gulf of California region during from the middle Miocene creation of a proto-Gulf, to the late Pliocene, when the region reached its modern configuration.

2. INITIAL STAGE

2.1. Middle Miocene Proto-Gulf

After 12 Ma, the strike-slip faulting migrated to the east of the batholith (Crowe 1978, Dokka and Merriam 1982, Barrash and Venkatakrishnan 1982, Stock and Hodges 1989). This change caused that by middle Miocene times, some areas in the northern part of the Gulf subsided below sea level (see Figure 3).

Microfossil data from oil exploratory wells in the northern part of the Gulf indicate marine deposition during middle Miocene times in Tiburón, Consag and Wagner

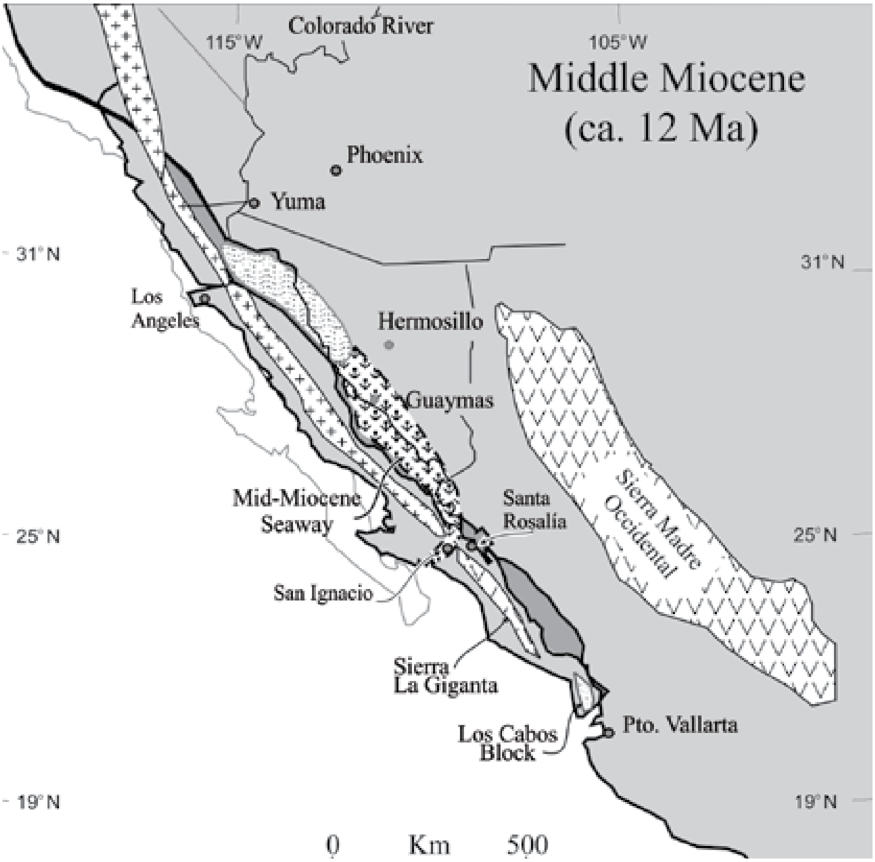

FIGURE 3. Approximate location and extent of the proto-Gulf and the approximate location of the Mid-Miocene seaway near San Ignacio, during the latter part of the middle Miocene (12 Ma).

basins (Helenes *et al.* 2009). These late middle Miocene microfossil assemblages represent the earliest marine sediments in the proto-Gulf area, which was formed in the eastern part of the Gulf, probably related to Basin and Range extension. A middle Miocene age for the earliest marine sediments in the area is controversial because it does not fit with some tectonic models which suggest the beginning of marine sedimentation in late Miocene times (Oskin *et al.* 2001, Oskin and Stock 2003).

The possibility for reworking these middle Miocene microfossils in samples from the exploration wells exists, but the microfossils must come from *in situ* stratigraphic sections yet undiscovered around the Gulf of California. In the areas surrounding the Gulf of California, the nearest middle Miocene marine sedimentary rocks crop out near San Ignacio, approximately 300 km southwest of Isla Tiburón, so it is unlikely that the reworking came from that area. Those outcrops belong to the San Ignacio Formation, which contains abundant marine megafossils, representing inner neritic facies, but to date, no planktonic foraminifera, calcareous nannofossils or dinoflagellates have been described from this unit (Carreño and Smith 2007). It is more probable that the reworking of the mentioned assemblages originated from within the proto-Gulf area.

Reports in the area of fossils older than late Miocene include nannofossils in the Salton Sea area (McDougall *et al.* 1999); foraminifera in Cerro Prieto (Cotton and Vonder Haar 1979) and dinoflagellates from Laguna Salada (Helenes-Escamilla 1999, Martín-Barajas *et al.* 2001). There are other reports of older Miocene diatoms from the Wagner basin (Rueda-Gaxiola *et al.* 1982), and planktonic foraminifera in south Sonora (Gómez-Ponce 1971). These reports of middle Miocene fossils in the area have been interpreted as reworking, because they are combined with younger fossils or in stratigraphic positions that indicate their reworked nature.

Paleogeographic models based on geophysical information (Lonsdale 1991, Bohannon and Parsons 1995), propose that the passage of seawater from the Pacific from the north or west was obstructed by the presence of the plutonic belt. Additionally, the paleoclimatic characteristics of the diatom assemblages from San Felipe (Boehm 1984) indicate tropical affinities (Esparza-Álvarez 1997, Esparza-Álvarez *et al.* 1998). This climatic affinity indicates that in the middle Miocene, the sea water must have entered from the south, similar to today's Gulf of California. Considering the extent of the main outcrops of the peninsular batholith, the mid-Miocene seaway was probably located between the Sierra San Pedro Mártir and the Sierra La Giganta (see Figure 3).

2.2. Late Miocene Oblique Extension

During the last part of the late Miocene (*ca.* 6 Ma) intensive volcanism took place at the Gulf, particularly along the eastern side of the Peninsula and in some Gulf islands (Martín-Barajas 2000). From the sedimentary point of view, by late Miocene to early Pliocene times, the proto-Gulf extended extensively toward the northern part of the area (see Figure 4).

To the north, the late Miocene marine basin reached into the Salton Sea area (McDougall *et al.* 1999), Laguna Salada (Martín-Barajas *et al.* 2001) and Altar Basin (Pacheco *et al.* 2006), and to the northeast near Yuma (Eberly and Stanley 1978). To the west it reached from the northern San Felipe-Puertecitos platform (Boehm

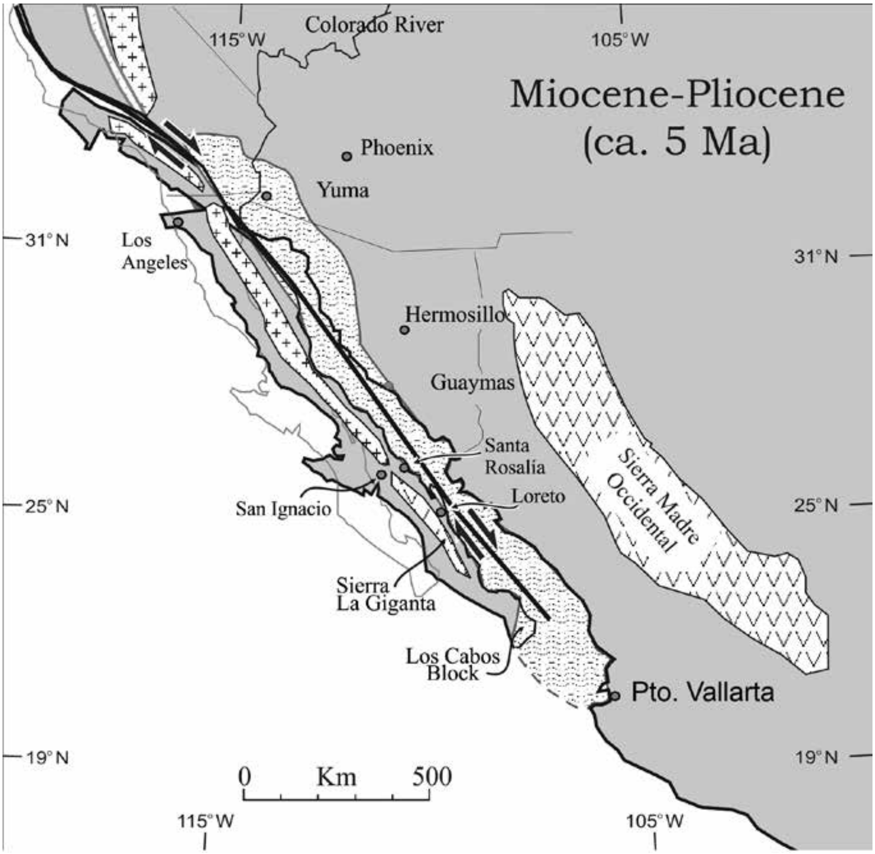

FIGURE 4. Location and extent of the Gulf of California at the beginning of the Pliocene (5 Ma).

1984, Martín-Barajas *et al.* 1997), to Santa Rosalía (Holt *et al.* 2000, Miranda-Avilés *et al.* 2005) in the central part of the Gulf. The eastern side of the Gulf also contains evidence of this late Miocene basin in Isla Tiburón (Smith 1991a, Gastil *et al.* 1999). In southern Sonora, there have been reports of marine sediments related to late Miocene basaltic flows in the vicinity of Hermosillo (Montijo-González 2000), in the Empalme Graben to the east of Guaymas (Roldán-Quintana *et al.* 2004, Marcos-Girón 2011).

The Miocene marine sedimentary units reported at the Los Cabos block (McCloy *et al.* 1988, Carreño 1992) and in the Islas Marias (Carreño 1985, McCloy *et al.* 1988) are more probably related to the Oligocene-Miocene marine units present in the Pacific side of Baja California Sur (Carreño and Smith 2007).

3. PRESENT STAGE

3.1. Late Pliocene Sea-Floor Spreading

Marine deposition on oceanic crust in the southern part of the Gulf itself began in late Pliocene time. Magnetic anomalies along the Tamayo Transform Fault have been dated at 3 Ma (Lonsdale 1991). Therefore, the southern mouth of the Gulf opened at that time, completely separating the Los Cabos block from mainland Mexico. For most of the Pliocene, the circum-Gulf region contains marine sedimentary rocks which represent essentially the actual Gulf of California. From the middle Pliocene (3 Ma) on, the present configuration of the region started and oblique extension occurred along strike slip faults and oceanic spreading in the Gulf itself.

The central part of the Gulf received marine sediments until early Pliocene times (Carreño 1982, Smith 1989, Dorsey *et al.* 1997), when a marine basin formed and reached its present extent by the late Pliocene. Marine outer neritic sediments are found near Santa Rosalía (Wilson 1948, Applegate and Espinosa-Arrubarena 1981, Carreño 1982, Smith 1989). In the vicinity of the Concepción Peninsula (Wilson 1948, Smith 1991a, b, Johnson *et al.* 1997, Ledesma-Vázquez *et al.* 1997), the Pliocene is represented by clastic alluvial to neritic deposits, with chert and limestones with mollusks and mangrove roots in the upper portions (Johnson *et al.* 1997). Near Loreto, the Pliocene is represented by deltaic to shallow marine sediments (McLean 1988, 1989, Umhoefer *et al.* 1994, Zanchi *et al.* 1992, Piazza and Robba1994, Dorsey *et al.* 1997).

Middle to late Pliocene marine deposits are found in Punta Chivato and on the islands between Santa Rosalía and Loreto, referred to as San Lorenzo, del Carmen, Montserrat and probably also on Coronado island (Durham 1950).

4. BIOGEOGRAPHIC DISCUSSION

Nowadays, the Peninsula and the Gulf of California contain a great marine and terrestrial biodiversity that is the result of biological process, particularly those related with the dispersion, isolation, origin and loss of species, all of them influenced by the geological history of the Baja California region. Most researchers involved in the regional evolution of southwestern North America accept that during late Miocene times a marine transgression coincident with a generalized rise in the sea level and the elevation of the isotherm formed a shallow embayment in NW Mexico, while the real Gulf started forming in the Pliocene. In the other side most part of biologists agree in consider this two mega geological events as responsible of two mega vicariate events.

According to the Neogene geologic evolution described above, in northwestern Mexico there were two main events which affected the existing biotas in different parts of the region. The first one took place between 12 and 6 Ma and is related to the formation of the proto-Gulf basin (see Figure 3). The second event took place from 6 to 3 Ma, when the sea transgression connected all the depressions and finally reached the modern configuration (see Figure 4).

This proto-Gulf basin was composed by a series of shallow, elongated depressions formed in mid-Miocene (12-11 Ma) times, from south-western Sonora to the central part of the actual Gulf, north of the midriff islands (Tiburón, Ángel de la Guarda, San Esteban). By late Miocene times (>10 Ma), the basins reached from southwestern Arizona to northeastern Baja California in the north, and to Santa Rosalía to the south. We believe that these basins were connected to the Pacific through a marine passage located somewhere south of the Sierra San Pedro Mártir. In the meantime, the southern part of the Peninsula was connected to mainland Mexico. The basins themselves starting to form two different biotas, one on Sonora to the east and another in Baja to the west.

Regardless of the age of the first marine sediments in the proto-Gulf, the phylogeographic signature of continental and shallow marine faunas in the modern Peninsula and around the Gulf indicates isolation of biotas during different periods and locations. This condition suggests the presence of barriers which effectively precluded migration of organisms during enough time so that they could diverge. Although there is no direct geologic evidence to define their precise location, the presence of marine transpeninsular passage ways is the most parsimonious and plausible way to isolate terrestrial and intertidal faunas (Hurtado *et al.* 2010).

A west to east seaway to connect the Pacific Ocean with the proto-Gulf (see Figure 3) has been proposed to have occurred during middle Miocene times in the center of the Peninsula near San Ignacio area (Helenes and Carreño 1999, Carreño and Helenes 2002). Some workers (Escalona-Alcázar *et al.* 2001, Oskin and Stock 2003) argue that no evidence has been found in the area, to support the presence of this seaway. However, no one has presented any evidence against it either.

Other researchers (Murphy and Aguirre-León 2002) have proposed that at 10 Ma the proto-Gulf was separated from the Pacific Ocean by a short peninsula, more or less equivalent to the state of Baja California or the northern half of the actual Peninsula. At the same time, the southern half was an archipelago and the Los Cabos region was still integrated to the continent. Then at ~7 Ma, a marine transgression invaded the Los Angeles Basin while the rest of the Peninsula was converted into an archipelago.

During the second event (6-3 Ma), the Peninsula separated completely from the continent (see Figure 4) giving rise to a second vicariant event. During this interval, at ~5 Ma, the Los Angeles Basin Sea receded and the Peninsula almost reached its actual configuration, except for the Los Cabos region where, they propose isolate land- mass very close to the continent. The existence of other, younger seaways have been proposed. One at 3 Ma to isolate the Los Cabos region from the rest of the Peninsula, and another one at ~1-1.6 Ma near the center of the Peninsula, which separated the biotas into two groups (Grismer 1994, Riddle *et al.* 2000).

The second event took place from 6 to 3 Ma, when the sea transgression connected all the depressions and finally reached the modern configuration (see Figure 4). To establish with any accuracy the precise timing of formation of the numerous islands forming the archipelagos, as well as the duration and extension of each step in this process has not been possible. Additionally, proposing the existence of seaways and islands or archipelagos is controversial because they do not seem to conform to current tectonic models, and because there is no direct geologic evidence to support their presence. Nevertheless, the phylogeographic characteristics of several groups from terrestrial and/or intertidal habitats clearly indicate that a separation of the populations took place following one of the geographic proposals mentioned before. So, to explain the origin and evolution of their actual diversity in the Gulf region, it is necessary to improve our understanding of the geological processes that produced the present landscapes, including the setting which fits with the actual biogeographic patterns.

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THE GEOLOGICAL FOUNDATIONS OF THE GULF OF CALIFORNIA REGION

Arturo Martín-Barajas*

To Gordon Gastil (1928-2012) for his major contribution
to the geology of northwestern Mexico.

The geological evolution of northwestern Mexico is marked by two tectonic and magmatic events: 1. The development of an Andean type subduction zone and its volcanic arc, and 2. An extensional episode that culminated with the rupture of the continental lithosphere along the Gulf of California. During Late Mesozoic and Late Cenozoic time (120-12 Ma) a long-lived subduction zone created magmatic arcs with volcanic eruptions over large regions in northwestern Mexico and southwestern United States. The magma bodies intruded older (Paleozoic-Mesozoic) sedimentary deposits along the margins of the North America craton adding a significant volume of new continental crust. During Late Cretaceous and Tertiary time (74-12 Ma) the continental crust was uplifted and deeply eroded along the Pacific margin and more than 10 km of vertical crust was striped away. A period of continental extension and coeval arc-volcanism and extension in Tertiary time (32 My to 12 Ma) produced the distinctive physiographic relief of basins and ranges in Sonora and Arizona. This occured simultaneously with the waning stage of arc-volcanism in the Sierra Madre Occidental and later along the Baja California Peninsula. Since ~12 Ma subduction ceased and crustal extension focused in a narrow belt along the Gulf of California capturing rivers, and allowing the first marine incursion and producing intermittent volcanic eruptions. Since ~3-4 Ma the narrow continental rift evolved to a proto-oceanic rift. This rifting event may have influenced the evolution of species when a new seaway formed, and landmasses were separated from the continent due to tectonic activity. New islands and prominent landforms emerged due to volcanic eruptions and block faulting during the ongoing phase of rifting.

1. INTRODUCTION

The geological substratum that supports the rich marine and terrestrial biodiversity and distinctive ecological niches in the Gulf of California region is predominantly composed of granitic and volcanic rocks, and sediments derived from these igneous rocks of various ages. This chapter summarizes the main geologic events that produced the geological foundations of the Gulf of California Extensional Province and its geologically young rift system. This chapter makes reference principally to landmark studies and publications concerning key recent findings, and although the cited bibliography is not exhaustive, this chapter provides the reader with a general overview of a long process of continental accretion and subsequent crustal stretching and rifting apart of Baja California from mainland Mexico.

2. TWO LANDMARK GEOLOGIC EVENTS AS TIME-DIVIDES

The geologic evolution of northwestern Mexico is marked by two main tectonomagmatic events that constitute useful time-divides to reconstruct its geological history. The first event was the onset of two sub-parallel magmatic arcs, and the second was the rifting of the continental crust and the formation of the Gulf of California.

The first event started during Late Jurassic to Late Cretaceous (163-90 Ma). The older of the two sub-parallel magmatic arcs is an oceanic arc active during Mid-Late Jurassic and Early Cretaceous that was accreted against the continental margin in Middle Cretaceous (Wetmore *et al.* 2003). Subsequently in Late Cretaceous a continental, Andean-type, magmatic arc developed due to collision and subduction of the Farallon oceanic plate beneath the North America continent. This continental arc produced intense volcanism fed by large magmatic intrusions along the western margin of North America. Its roots are the granitic bodies that form the peninsular ranges batholith (PRB) and the coeval but somewhat younger Laramide batholith of Sonora and Sinaloa (McDowell *et al.* 2001, Henry *et al.* 2003, Ortega-Rivera 2003). The peninsular ranges batholith is continuously exposed from southern California to mid-Baja California, and further south where it is likely covered by 1-1.5 km-thick Tertiary volcanic and sedimentary deposits north of La Paz in southern Baja California (see Figure 1). This granitic belt crops out again in the Los Cabos block in southernmost Baja California and continues in mainland Mexico south of Puerto Vallarta and along the Pacific margin of southern Mexico (see Figure 1). The granitic intrusives are also exposed over Sonora and Sinaloa and lie beneath the volcanic cover of the Sierra Madre Occidental (McDowell *et al.* 2001, Henry *et al.* 2003).

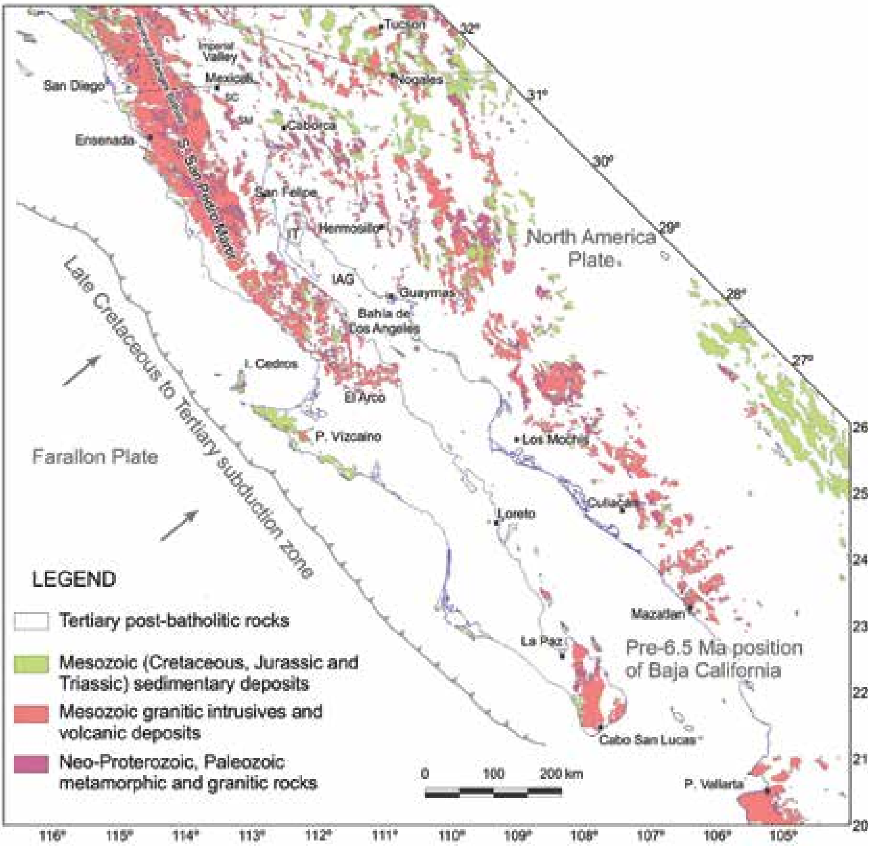

FIGURE 1. Simplified geological map of northwestern Mexico and southwestern United States. Only batholitic and prebatholitic rock units are shown for simplicity. Note the N-NW trending basin and range physiography in Sonora and Arizona that resulted from mid to late Tertiary extension. Baja California is ~250 km south of its present position prior to the onset of oblique rifting (*ca.* 7 Ma). Additional 250 to 300 km are required to close the mouth of the Gulf. Geological map adapted from INEGI 1:1000,000 geological maps and USGS 1:1,000,000 geological maps of Arizona and California.

The second event that marks the geologic history of northwesten Mexico is the rifting process that culminated in the formation of the Gulf of California, which started about 12 million years ago, but was well established along its present length by ~6.5 ma (Oskin and Stock 2003). This phase of continental rifting developed along the ancient suture between an essentially Mesozoic magmatic arc-terrain to the west, and the Proterozoic-Paleozoic cratonic margin to the northeast.

Based on these two tectonomagmatic events, we refer to pre-batholitic rocks as the rock units formed prior to and metamorphosed by Late Jurassic to Late Cretaceous magmatic intrusions (see Figure 1). Post-batholitic rocks are subsequently divided into rocks units formed during latest Cretaceous and Tertiary times (65 to 25 Ma), and rock units formed during and after the Oligocene to Middle Miocene (25-12 Ma) extensional event that stretched the continental crust simultaneously with the waning stage of arc volcanism. Extension of the crust affected a broad region in Sonora and Sinaloa but subsequently (*ca.* ~12 Ma) the extension focused along a narrower region that rapidly subsided and conducted the first marine incursion in the Gulf of California. We thus subdivide the post-batholitic geologic record in two stages; pre-rift and syn-rift stages. Pre-rift rocks are principally arc-related volcanic and volcaniclastic deposits of the Sierra Madre Occidental and the Comondú arc in Baja California (23-12 Ma). Syn-rift rocks are mainly sedimentary and volcanic deposits formed during the current phase of active rifting. This rifting event resulted in the progressive capture of the Baja California Peninsula by the Pacific Plate and defined the modern transtensional boundary between the Pacific and North America plates along the Gulf of California and the San Andreas fault system.

A summary of the main characteristics of the rock units, and their tectonic settings before, during and after the two principal tectonomagmatic events is presented bellow.

2.1. Pre-Batholitic Geology

The evolution of the Proterozoic and Paleozoic continental margin of southwestern North America has been depicted from studies along discrete localities in Baja California (see compilation of papers in Gastil and Miller 1993), and more extensively in Sonora (Stewart *et al.* 1997, 2001, Gehrels and Stewart 1998, Iriondo *et al.* 2004) and Arizona, Nevada, and California (Gehrels 2000, Stewart *et al.* 2001) (see Figures 2a and 2b).

During Paleozoic time (570-245 Ma) the southwestern margin of the North America craton was located in present Arizona-Sonora and eastern California and Nevada (see Figure 2a). The continental crust that forms the contemporary Baja California Peninsula did not exist at that time. Shallow marine and deep marine sediments of Paleozoic and Mesozoic Era were deposited as recorded at several locations in eastern Baja California, Sonora and southern California (see Figures 2a, 2b and 3). These sedimentary deposits accumulated over a composite Proterozoic-Paleozoic continental shelf and slope (Gastil 1993, Stewart *et al.* 1997), and were metamorphosed principally during emplacement of Jurassic and Cretaceous plutonic rocks.

The oldest rocks in Baja California crops out near the town of San Felipe (see Figure 2). An Early Paleozoic age of a quartzite and mafic schist was established

FIGURES 2. Schematic distribution of Paleozoic and Mesozoic sedimentary facies in northwestern Mexico before rifting in the Gulf of California (adapted from Gastil 2003): (a) late Proterozoic-Early Paleozoic Miogeoclinal facies and reported localities. (b) Distribution of Triassic, Jurassic and Cretaceous sedimentary and volcanic deposits in northwestern Mexico. This figure shows the area of volcanic deposits of the Late Jurassic to Early Cretaceous Alisitos arc to the west and terrigenous sediments derived from continent to the east. FIGURE 2A (ABOVE)

from lithologic and stratigraphic correlations with well-dated Pre-Cambrian and Early Paleozoic rocks near Caborca in Sonora (Anderson 1993, Stewart and Pole 2002) and Death Valley region in California (Stewart *et al.* 2001). In the southern flank of Sierra San Pedro Martir similar metamorphic rocks are exposed and lie within a belt of Proterozoic and Paleozoic terrigenous and carbonate rocks extending from central Nevada to Sonora (see Figure 2a). Paleozoic deep-water facies are common in Baja California and quartzite and marble are more common in Sonora were shallower marine sedimentary environments developed over the cratonic

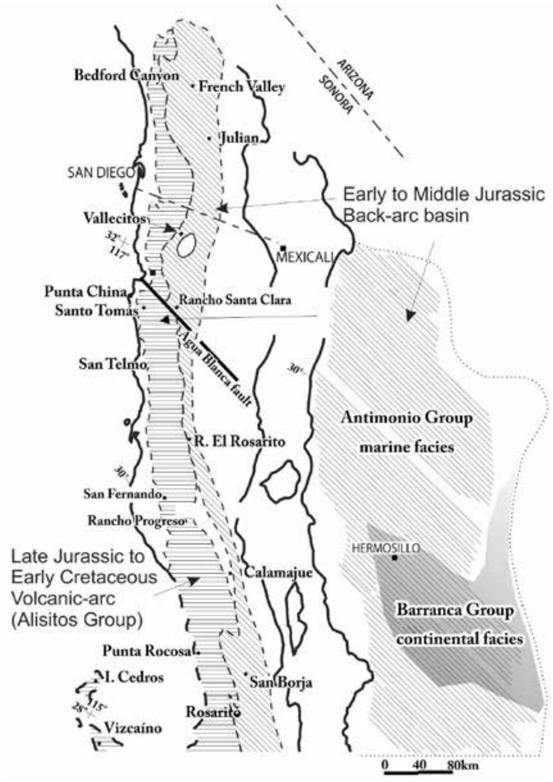

FIGURE 2B.

continental shelf. These Late Precambrian and Paleozoic rocks correspond to continental shelf-slope deposits along the margins of the North American craton, and imply that central and northwestern Sonora contains a Proterozoic cratonic basement that accumulated Paleozoic marine deposits along its margins (Stewart *et al.* 2001, Valencia-Moreno *et al.* 2001).

During the Mesozoic time shallower marine conditions existed in Sonora and Arizona while deeper marine conditions occurred in present Baja California and California (see Figure 3). Triassic and lower Jurassic continental and marine deposits in Sonora are grouped into de Barranca Group and Antimonio Group, respectively (González-León *et al.* 2009). The Antimonio Group includes chiefly shallow marine carbonate and terrigenous sequences located on the continental shelf that surrounded deltaic and fluvial sedimentary environments represented in the Barranca Group. The Antimonio and Barranca groups overlie the Paleozoic (Permian), dominantly calcareous deposits represented by the Monos Formation in Sierra El Alamo of northwestern Sonora (González-León *et al.* 2009). The slope facies and deep basin environments were located toward the west and southwest (*e.g.* San Marcos in

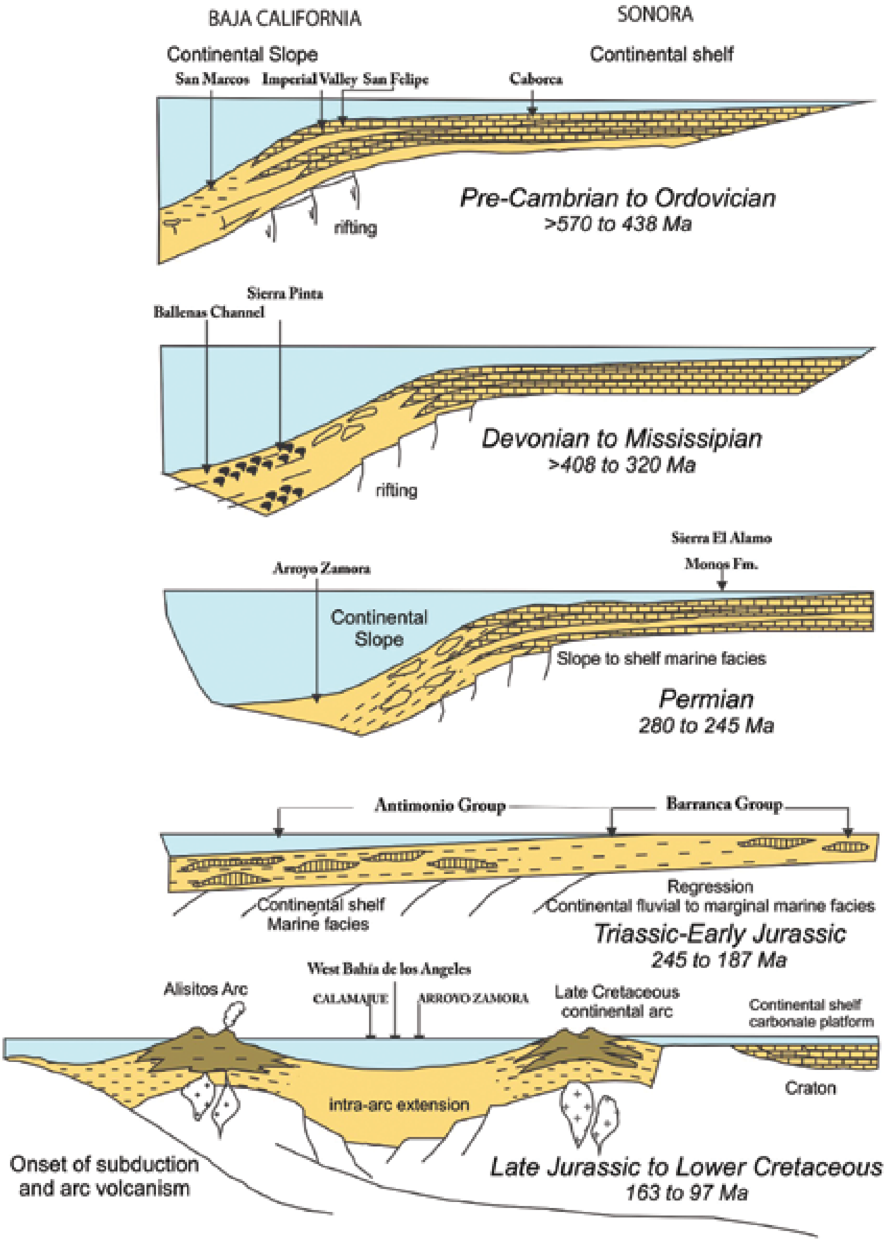

FIGURE 3. Schematic cross-sections of facies distribution across the southwestern margin of the North American craton. Note that carbonate and quartzose sediments dominate the eastern continental shelf in Sonora, whereas deep-water sedimentary facies dominate to the west (slope and basin sedimentary environments). In Late Jurassic and Early Cretaceous a volcanic arc developed as consequence of subduction of the Farallon Plate under North America (modified from Gastil and Miller, 1993).

northern Baja California and Bedford Formation of southern California) were the typical sandstone, siltstone, and mudstone, mostly turbidite deposits includes large exotic blocks (olistostrome) transported in mass flows deeper across the continental slope (c.f. Lothringer 1993).

The relevance of these medium to high-grade metasedimentary rocks is their contribution to reconstruct the paleo-geography of the southwestern continental margin. For the biosphere that supports the circum-Gulf region its relevance is probably their high-alumina content of phyllosilicates derived from dominantly pelitic, clay-rich mudstone deposits and were progressively buried several kilometers and metamorphosed during large igneous intrusions in the Cretaceous time.

2.2. Onset of subduction and arc volcanism

The southwestern margin of the North American continent contains the record of two parallel but diachronous episodes of subduction and arc-volcanism that were tectonically juxtaposed during Mid- to Late Cretaceous time (see lower schema in Figure 3). The westernmost and older volcanic arc is allochthonous and is of oceanic affinity. It is thought to have formed in an island arc setting (subduction involving two oceanic plates) west, but at an unknown distance from the continent (Gastil 1993, Wetmore *et al.* 2003, Umhoefer 2003). This Late Jurassic to Early Cretaceous volcanic arc has two episodes of volcanism: one crops out in the Cedros-Vizcaíno and El Arco areas (see Figures 1 and 2b); a second episode crops out along the Pacific margin past-north latitude 28°N in the Baja California Peninsula (the Alisitos arc) and southward in the Pacific margin of southern and central México (Centeno-García *et al.* 1993, Talavera-Mendoza *et al.* 2007, Escalona-Alcázar *et al.* 2009).

At the Vizcaíno Peninsula, and Cedros Island a sequence of Late Jurassic-Early Cretaceous sedimentary arc-related volcaniclastic rocks overlie a Triassic ophiolite (oceanic) basement intruded by Middle-Jurassic to Early Cretaceous granitic intrusives. The volcanosedimentary sequence and granitic intrusions constitutes the first evidence of oceanic arc - continent interaction in the Pacific margin of Baja California (Kimbrough and Moore 2003).

The easternmost evidence of this early oceanic arc has been found in east-central Baja California. Mafic intrusives at El Arco-Calmalli (see Figure 1), and mafic to intermediate lava flows at Arroyo Calamajue (see Figure 2b) are likely related to this phase of island-arc volcanism (Griffith and Hobbs 1993). At Calamajue the lava flows unconformably overlie quartz-rich sedimentary rocks derived from the North American craton to the east and constitute additional important evidence of the interaction between the island-arc and a basin that received quartzose detritus from the continent to the west. At El Arco a mafic intrusive dated at ~165 Ma (Weber and López-Martínez 2006) contains the geochemical and isotopic signature of an oceanic island-arc intrusive. This mafic dioritic rock is probably one of the oldest magmatic intrusions related to an early stage of the Alisitos volcanic arc, and clearly predates subsequent emplacement of the tonalitic plutons that dominated the continental arc thereafter.

In Baja California, the Early Cretaceous volcanic arc with oceanic affinity is the Alisitos arc. This volcanic arc accumulated >6 km of volcanic and sedimentary deposits at the type locality of the Alisitos Formation in Santo Tomas 20 km south of Ensenada (Allison 1974). This Early Cretaceous volcanic and sedimentary succession crops out continuously along the western side of the Peninsula (see Figure 2b), where it also includes intermittent reefal carbonates and volcanogenic sedimentary deposits, which likely developed during periods of volcanic quiescence (Suárez-Vidal 1987).

The Alisitos arc and its somewhat northern equivalent the Santiago Peak Volcanics of southern California both represent an island arc tectonically accreted to the western margin of the North America continent during Late Jurassic to Mid-Cretaceous time (see summary in Wetmore *et al.* 2003). Syn-batholitic crustal shortening occurred between 115 and 108 Ma in the Sierra San Pedro Martir region (Johnson *et al.* 1999). A change in the mineralogical and geochemical composition of the intrusive rocks of Late Cretaceous age indicates a change to continental arc magmatism (Andean type). This compositional change is well defined from west to east and has alternatively been explained in terms of a volcanic arc crossing a pre-existing Late Jurassic to Early Cretaceous oceanic-continental boundary (Thomson and Girty 1994, Todd *et al.* 2003). The suture of these two volcanic arcs follows the axis of the Baja California Peninsula and is defined by a distinctive contrast of two types of plutonic bodies. To the west, plutons are commonly zoned and composed of gabro, diorite and tonalite all containing magnetite as the principal iron oxide phase. In contrast, the eastern plutonic belt is characterized by tonalite and granite intrusives with ilmenite (Fe-Ti oxide) as a distinctive mineral phase. The boundary between these two suites of plutonic belts defines the magnetite-ilmenite boundary, which is a distinctive magnetic feature along the peninsular ranges batholith (Gastil *et al.* 1990). This lineament crudely defines the boundary between the Alisitos arc and its oceanic lithosphere to the west and the tonalitic plutonic belt with a continental lithosphere to the east.

The continental arc developed in Late Cretaceous along the edge of continental margin and magmatism progressively migrated eastward during Late Cretaceous and Early Tertiary time (Ortega-Rivera 2003, Todd *et al.* 2003) (see Figure 4a). In Sonora and Sinaloa Late Cretaceous-Paleogene volcanic and plutonic rocks were

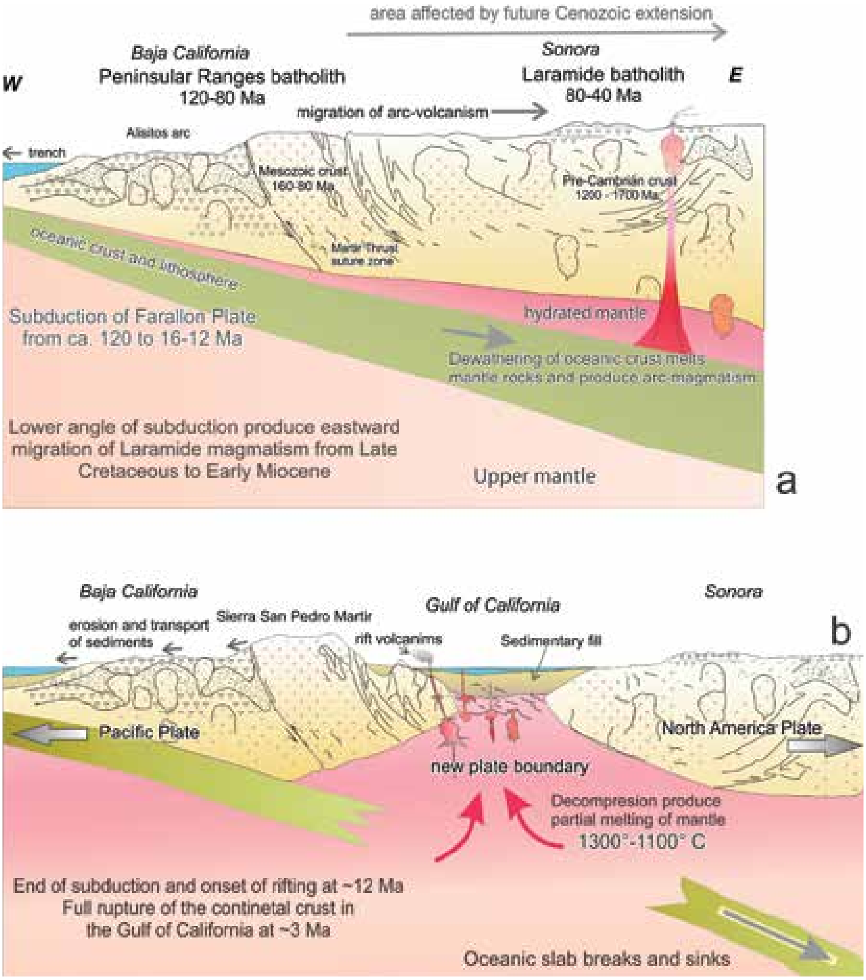

FIGURE 4. Schematic West to East cross section of the continental crust of northwestern Mexico (a) during subduction of Farallon Plate (above), and (b) during rifting and rupturing of the continental crust in the Gulf of California within the last three to four million years.

emplaced as part of the cordilleran magmatism temporally associated with the Laramide contractional deformation in the western United States and Canada (see Figure 4a). Significant magmatic activity in the coastal region of Sonora and Sinaloa is coeval with the peninsular ranges batholiths and indicates that the early stage of the continental arc occupied both Baja California and coastal Sonora and Sinaloa regions (Henry *et al.* 2003, Ramos-Velázquez *et al.* 2008). However, plutonic rocks tend to be progressively younger eastward across Sonora; varying from 90-70 ma in the coastal region to predominantly ~55-75 Ma beneath the western flank of the Sierra Madre Occidental (Coney and Reynolds 1977, Damond *et al.* 1983, Roldán *et al.* 2009). In contrast radiometric ages in granitic rocks in Baja California are older and range from 80 to 110 Ma (Ortega-Rivera 2003).

The plutonic and volcanic rocks produced in Sonora and Chihuahua expands from Late Cretaceous to Paleogene during the Laramide contractional event (see Figure 4a). The Paleogene plutonic and volcanic are rocks are collectively grouped into the Lower Volcanic Complex of the Sierra Madre Occidental by McDowell and Keizer (1977). Exposures of the Lower Volcanic Complex coeval with Laramide plutonic rocks are widespread over considerably wider areas in the north compared to southern Sonora and Sinaloa. This difference is likely related to a larger amount of Oligocene to Miocene extension in north-central Sonora that in southern Sonora and Sinaloa (see Figure 4).

The Laramide magmatic event and the rocks it formed in Sonora is also important because of the mineralization of Cu, Mo and Au that accompanied the associated hydrothermal circulation and cooling history of intrusive rocks (Damon *et al.* 1981, Clark *et al.* 1982, Pérez-Segura *et al.* 2009).

In summary, during Cretaceous and Tertiary time plutonic bodies metamorphosed and amalgamated Paleozoic and Mesozoic sedimentary deposits previously deposited over the continental shelf across western Sonora, Sinaloa, Baja California and southwestern United States (Figure 4a). This cretaceous magmatic arc represents a significant volume addition to the continental crust along the southwestern margin of the North America continent.

3. POST BATHOLITIC GEOLOGIC HISTORY PRIOR TO RIFTING (50-25 MA)

The sub-aereal volcanic rocks genetically linked to the dominantly tonalitic plutons were deeply eroded during the latest Cretaceous, Paleogene and Neogene times due to uplift of the continental crust; more than 10 km of vertical crust in both southern California and Baja California was eroded during progressive exhumation (Ortega-Rivera 2003, Symons *et al.* 2003, Grove *et al.* 2003). The resultant detritus of this vast erosion was transported to the Pacific continental shelf and slope-trench system where these sediments subducted beneath the continental crust or remained stored at the accretionnary prism above the subduction zone. This sedimentary wedge also widened the continental shelf of western North America.

During Oligocene and Early Miocene time the volcanic arc stalled along the Sierra Madre Occidental and accumulated >2 km of rhyolite to dacite pyroclastic

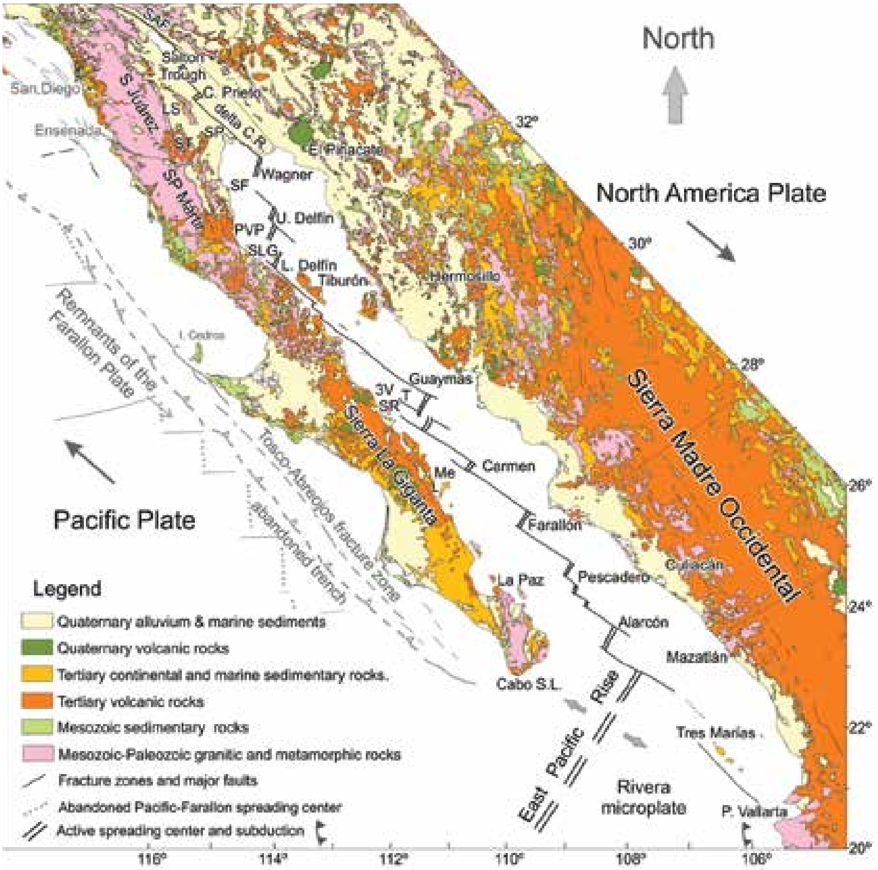

FIGURE 5. Geologic and tectonic map of northwestern Mexico. The granitic and metamorphic rocks form the continental crust. The Sierra Madre Occidental and a large area in Baja California (Sierra La Giganta) contain most of Miocene arc volcanism in northwestern Mexico. Several synrift volcanic fields overly arc-related volcanic deposits and basement rocks. Tectonic features offshore the Pacific Ocean are abandoned spreading ridges, fracture zones and remnants of the Farallon Plate that failed subduction beneath the North American Plate. The West Baja Shear zone is the Tosco-Abreojos fault zone, interpreted to accommodate part of the Pacific-North America plate motion during the opening of the Gulf of California. SAF San Andreas fault, C.R. Colorado River, LS Laguna Salada, LT Sierra Las Tinajas, PVP Puertecitos Volcanic Province, SLG San Luis Gonzaga, 3V Tres Vírgenes, SR Santa Rosalía, T Isla Tortugas, Me Mencenares volcanic field.

deposits (ignimbrites) and lava domes forming what is known as one of the largest rhyolitic volcanic provinces on Earth (McDowell and Clabaugh 1979, McDowell *et al.* 2001, Ferrari *et al.* 2002).

During Middle Miocene most of the Farallon oceanic plate was nearly consumed, and the Pacific-Farallon ridge progressively encountered the subduction zone along the Pacific margin (see Figures 4a and 4b). This plate reconfiguration was accompanied by two major geological events: 1. The progressive ending of arc volcanism in northwestern Mexico and southwestern United States, and 2. A process of intra-arc extension of the continental crust. This last event progressively conducted to rifting along the Gulf of California corridor.

4. THE RIFTING STAGE AND THE PROTO-GULF OF CALIFORNIA

The Cenozoic extensional event in southwestern United States and northwestern Mexico that preceded rifting in the Gulf of California has been attributed to various causes; *e.g.* gravitational collapse of over-thickened crust, mantle upwelling due to slab-free window, and relaxation of confining stresses due to plate reconfiguration in the Pacific margin. These processes are not mutually exclusive and probably all played a role in producing large amounts of extension of the continental crust over a vast region in southwestern United States and northwestern Mexico. This extensional event originated the Basin and Range Extensional Province, which also comprises the region of northwestern Mexico surrounding the Sierra Madre Occidental (see Henry and Aranda-Gómez 1992), and includes the Gulf of California Extensional Province (see Figure 5).

The Gulf Extensional Province is the southwestern part the Basin and Range Province, and for practical purposes its eastern boundary is the topographic escarpment of the Sierra Madre Occidental. The western boundary is the topographic escarpment along the eastern side of the Peninsula, which is also known as the Main Gulf Escarpment along the Sierra Juárez and Sierra San Pedro Mártir (see Figure 5). The Gulf Extensional Province in turn surrounds the Gulf of California, which represents the narrower and younger stage of the ongoing proto-oceanic stage of rifting. Most pre-rift volcanic and sedimentary deposits that once covered the crystalline basement were severely faulted and eroded during the Miocene extensional event that produced the distinctive basin and range topography in Sonora and Arizona (see Figures 4 and 5). This province is characterized by a series of northwest to north-south trending mountain ranges composed of igneous and metamorphic rocks separated by broad elongated valleys filled with alluvial deposits derived from erosion of uplifted blocks (see Figure 5). There, the ranges are bounded by normal faults oriented along the range fronts. Many of these faults dip shallow (<30°) and typically accommodated large-magnitude of extension during the Middle Miocene. This early period of extension overlaps in time with the waning stage of arc volcanism in the Sierra Madre Occidental (32-19 Ma), and along the Baja California Peninsula between 20 and 12 Ma (Martín-Barajas 2000, Ferrari *et al.* 2007).

A peak of extension in central Sonora occurred in Late Oligocene to Middle Miocene time (Nourse *et al.* 1994, Gans 1997), and extreme crustal extension produced significant footwall uplift in detachment faults. The resultant metamorphic core complexes in central Sonora expose middle to lower crustal levels due to uplift during the 25 to 12 Ma time spans (Nourse *et al.* 1994). This time constraint is also consistent with age dating in continental basins in Sonora with mid-Miocene interbedded basaltic lava flows (McDowell *et al.* 1997).

In northwestern Sonora and southwestern Arizona a pulse of extension named "Late Miocene block faulting episode" by Eberly and Stanley (1978), produced basin and range structures and thick continental and lacustrine deposits in the Yuma basin between ~13 and >10.5 Ma. This is also consistent with the post-17 Ma age for widespread normal faulting in the Yuma area proposed by Spencer *et al.* (1995).

In the Salton Trough of southern California and northern Baja California Miocene sedimentary and volcanic deposits dated between 22 and 12 Ma record a first phase of weak extension and high-angle normal faulting (Winker and Kidwell 2002). This early period of weak extension predated the Late Miocene to Pliocene phase of high-magnitude extension and rift-basin development (Winker and Kidwell 1996, Axen and Fletcher 1998). In the southwestern Salton Trough and the Laguna Salada area (see Figure 5) the Late Miocene phase of high-magnitude extension occurred along detachment fault systems (Axen and Fletcher 1998, Winker and Kidwell 2002). The Laguna Salada detachment system is likely to be active and kinematically linked with strike-slip faults of the northern Gulf of California (Axen *et al.* 1999, Fletcher and Spelz 2008).

In northern Baja California the onset of Miocene extension is constrained by faults that cut arc-related volcanic rocks dated at approximately 16 Ma in the range front of southern Sierra Juárez (Lee *et al.* 1996) and lava flows and tuffs from Sierra Las Tinajas dated 10.5 and 12 Ma, respectively (Mendoza-Borunda *et al.* 1998). These crosscutting relationships provide a maximum age of 12 Ma for the onset of extension along the Main Gulf Escarpment in northern Baja California. Additionally, cooling ages of crystalline rocks on Sierra El Mayor at the western edge of the delta-plain of the Colorado River and on Sierra San Felipe constrain the early uplift and exhumation of this intra-rift crystalline block between 10 and 7 Ma (Axen *et al.* 2000, Seiler *et al.* 2010).

5. THE PROTO GULF OF CALIFORNIA

During Late Miocene (<12 Ma) the broadly distributed extension that affected most of Sonora and southern California and Arizona became localized towards the west in a narrow zone that rapidly subsided and promoted the first marine incursion in the Gulf of California (see Figure 4b). Current field studies look for evidence of the timing of the first marine incursion, and for when and how strike-slip motion was fully transferred from the Pacific margin into the Gulf of California corridor (c.f. Stock and Hodges 1989, Fletcher *et al.* 2007). This event progressively occurred between 12 and 6 Ma when the Pacific margin also acted as a plate boundary along the Baja California shear zone (also named the Tosco-Abreojos fracture zone). The southward "jump" of the Rivera triple junction and subsequent propagation of the East Pacific Rice (EPR) northward into the mouth of the Gulf defined the new plate boundary (Curry and Moore 1984, Lonsdale 1991). An important implication is that mantle upwelling and thermal expansion of the lithosphere focused along the old boundary between the Late Cretaceous volcanic arc and the North American craton, which had been previously heated and weakened during the waning stage of arc-magmatism in the late Middle Miocene. These conditions may have controlled the definition of the new plate boundary, thus transferring the Baja California Peninsula to the Pacific plate.

The concept of the proto Gulf of California was first introduced by Karig and Jensky (1972) to refer to the early period of extension in the Gulf of California as an analog to other "volcano-tectonic rift zones associated with an active trench-arc system". This concept is analogous to the concept of intra-arc and/or back-arc basins. Subsequently, the term proto-Gulf was used as a synonym of the early marine basins and to name the early period of orthogonal extension and basin development (Gastil *et al.* 1975, Stock and Hodges 1989). However, the main discussion among scientists has centered on when this process of back-arc extension of the crust conduced the inflow of marine waters during the early stage of the Gulf of California or proto-Gulf stage. The proto-Gulf of California was considered to be older than 12 Ma (Middle Miocene) because volcanic deposits overlying a marine sequence at Isla Tiburón yielded that age (see Gastil *et al.* 1979). However, Oskin and colleagues (2001) proved that previous stratigraphic relationships were wrong and a younger age for the same marine section at Isla Tiburón (<6.2 Ma) was obtained. Age constraints at other sites with marine deposits around the Gulf margins are consistent with the <6.5 Ma age for the Isla Tiburón marine sequence and hence the first marine incursion in the northern Gulf of California may have occurred after 7 Ma, when the boundary between the Pacific and North American plates shifted into the Gulf region (Oskin and Stock 2003).

The Late Miocene age for the first marine incursion in the Gulf (*ca.* 7 Ma) is widely accepted because it is also consistent with tectonic reconstructions of the Baja California Peninsula prior to 6.5 Ma. The correlation of pyroclastic deposits (ignimbrite) dated 12.5 and 6.5 Ma, respectively, and distinctive fluvial conglomerates require the Sonora margin being adjacent to the Baja California Peninsula prior to 7 Ma (Gastil *et al.* 1975, Oskin *et al.* 2001, Oskin and Stock 2003). Outcrops of these tuffs are found in both margins across Upper Delfin and Tiburón basins, and represent ~260 km of northwestward tectonic transport of Baja California to account for the opening of the Gulf of California during the current phase of oblique rifting. However, there are more than 250 km of oblique extension to account for in order to fully close the mouth of the Gulf (see Figures 1 and 5). This extension probably occurred along the margin of Sonora and Sinaloa and in a lesser amount along the coastal region of Baja California Sur sometime prior to ~7 Ma.

Recent paleontological studies in cutting samples of exploration wells from PEMEX indicate the presence of microfossils of Middle Miocene age in Tiburón, Upper Delfin and Wagner basins (Helenes *et al.* 2009, Helenes and Carreño, this volume). These findings raise again the controversy about the age of the proto-Gulf and maintain the likelihood of an older mid-Miocene age for the first marine incursion. The possibility for reworking these Middle Miocene microfossils in exploration wells exists, but the microfossils must come from *in situ* stratigraphic sections yet undiscovered around the Gulf of California.

The corollary of these new findings is that mid-Miocene marine deposits (*e.g.* Helenes *et al.*, 2009; Helenes and Carreño, this volume) contradict the <6.5 Ma age for the onset of oblique extension based on the correlation of volcanic and sedimentary units across the Gulf of California (Oskin *et al.* 2001) and from age-compilation of marine deposits around the Gulf margins, which is consistent with a <6.5 Ma age for the first marine incursion in the Gulf (Oskin and Stock 2003). Deciphering when Baja California started to move northwestwards and when it was fully detached from North America has important implications to understand the rheological behavior of the lithosphere under different rates of strain. Based on the ~6.5 onset of oblique extension we can conclude that the Gulf of California is a young and fast rift system, which currently records ~51 mm/yr of relative plate motion across the Pacific and North America (Plattner *et al.* 2007).

6. THE DELTA OF THE COLORADO RIVER

A major event in the history of the Gulf of California region is the capture of drainage discharge of the Colorado River in the Salton Trough and the northern Gulf of California by the end of the Miocene time. Field studies in the western Salton Trough and NE Baja California indicate that Pliocene fluvio-deltaic deposits from the Colorado River prograded over Late Miocene marine basins (Dibblee 1984, Winker and Kidwell 1996, Pacheco *et al.* 2006). The change from marine to fluvio-deltaic environments in the Salton Trough is well documented to have occurred by ~5.5 Ma (Dorsey *et al.* 2011); however, what is still a matter of debate is the establishment of an integrated course of the Colorado River that may have occurred either by headward erosion or by lake overflow near Lake Mead. Whatever the mechanism of integration of fluvial drainage, field studies indicate that the course of the Colorado River below Grand Wash and the site of the Hoover Dam established post 6 Ma and pre 4.3 to 4.8 Ma. This age interval marks the time when the upper Colorado River integrated its course with the lower Colorado and drainage from the Rocky Mountains reached the Gulf of California. This process dramatically increased the sediment supply and the growth-rate of the delta of the Colorado River.

7. THE TRANSITION FROM ARC TO RIFT VOLCANISM

The end of arc volcanism in the Sierra Madre Occidental is ~19 Ma ago (Ferrari *et al.* 2002) and thus overlaps in time with the onset of extension of the continental crust in central Sonora recorded between 27-12 Ma (Nourse *et al.* 1994, Gans 1997). During this time the volcanic arc retreated to eastern Baja California and remained active from 20 to 16 Ma in both northern and southern Baja California. The volcanic record in coastal Sonora and Sinaloa is also this age although less well preserved. Progressively the volcanic arc ended during a waning stage in southern Baja California from 16 to ~12 Ma (Hausback 1984, Sawlan 1991, Martín-Barajas *et al.* 2000, Umhoefer *et al.* 2001).

The transition from subduction to rifting is accompanied by a change in the type of volcanic eruptions and composition of magmas. Pre-rift mid-Miocene arc volcanism in Baja California is characterized by composite strato-volcanoes of dacite to andesite lavas that produced large volcano-sedimentary aprons due to their high relief and explosive events (Gastil *et al.* 1979, Hausback1984, Martín-Barajas *et al.* 1995, 2000, Umhoefer *et al.* 2001). Several of these pre-rift volcanic deposits are still preserved in northern Baja California beneath syn-rift volcanic and sedimentary deposits (*e.g.* Puertecitos volcanic province, San Luis Gonzaga, and Isla Ángel de la Guarda (see Figure 5). In contrast arc volcanism formed a continuous volcanosedimentary sequence in Baja California Sur, where the volcanic succession is the Comondú arc, which is more that 1000 m-thick in southern Baja California and forms the abrupt relief in Sierra La Giganta (see Figure 5). The Comondú arc represents the waning stage and end of subduction along the Pacific margin offshore Baja California (Hausback 1984, Umhoefer *et al.* 2001).

After subduction ceased, syn-rift volcanism changed dominantly to bi-modal rhyolitic-basaltic in composition. Volcanic eruptions chiefly produced rhyolite ignimbrite deposits and lava domes in Late Miocene and Pliocene volcanic fields in the margins of the Gulf of California (*e.g.* Sierra Las Pintas, Puertecitos, Isla San Esteban; Mencenares; see Figure 5). Also andesitic to dacitic composite volcanoes and calderas (*e.g.* Tres Vírgenes volcanic field) are local distinctive syn-rift magmatic events. This silicic to intermediate volcanism was accompanied with basaltic and andesitic lava flows and small scoria cones mostly in areas west of the zone of extension beyond the main Gulf escarpment from 10 M.a. to Recent in central and southern Baja California. Late Miocene to Quaternary basaltic lavas also emplaced along the coast of Sonora and Sinaloa (Mora-Álvarez and McDowell 1995, Henry and Aranda-Gómez 2000, Paz-Moreno *et al.* 2003).

Subaereal volcanic eruptions have intermittently occurred in the margins of the Gulf in Pleistocene time (<1.6 Ma), and some volcanoes emerged from underwater or throughout the sediments on both the submerged continental margins (*e.g.* Isla San Luis; Isla Coronado) or on the axial deep troughs (Isla Tortuga, Roca Consag; Cerro Prieto, Salton Buttes; see Figure 5).

Offshore the most recent volcanic eruptions have occurred mostly within tectonically active rift basins and its margins. Basaltic lava dominates the volcanic activity in deep basins in the southern Gulf of California. These basins are nascent spreading centers floored with both basaltic lava-flows fed through dikes and lava flows from a central vents. Other vents have formed submarine shield volcanoes emerging from the ocean (e.g Isla Tortuga, c.f. Batiza *et al.* 1979).

North of the mid-drift islands the inflow of Pliocene to Pleistocene terrigenous sediments from the Colorado River has been very high and sedimentary deposits reach several kilometers-thick (Pacheco *et al.* 2006, Aragón-Arreola and Martín-Barajas 2007). The less dense sedimentary rocks cap the new crust and prevent dense basaltic magmas from reaching the surface and forcing them to differentiate at depth. This has produced lower density magmas that overcome the sediment lithostatic load and may ascent to shallower levels, and eventually erupt andesite dacite and rhyolite lavas. Geochemical and Sr-Nd and U-Th and U-Pb isotopic data indicates that magmatic differentiation from basalt to andesite and rhyolite may take place either by partial melting of gabbroic (basaltic) magmas (Schmitt and Hulen 2008, Schmitt *et al.* 2013), or by crystal fractionation with minor contamination of continental crust and sediments (Herzig and Jacobs 1994, Paz Moreno and Demant 1999, Martín-Barajas *et al.* 2008).

The Tres Vírgenes volcanic complex north of Santa Rosalía, Baja California Sur is a Quaternary volcanic field that includes three synrift stratovolcanoes and two caldera structures (see Figure 5 for location). The geochemistry and the style of volcanic eruptions in stratovolcanoes and calderas mimic the activity of the extinct arc volcanism around the Gulf of California. The highest volcano is La Virgen (~1900 m high) whose last eruption occurred less than 34 ky (Schmitt *et al.* 2006). The two large calderas (La Reforma and Aguajito) predate the activity of Las Virgenes volcanoes, but erupted less than one million year ago (Garduño-Monroy *et al.* 1993). This young volcanic complex is potentially hazardous although in recent years it also provides geothermal energy to the town of Santa Rosalía. Other Late Pliocene and Pleistocene volcanic eruptions have occurred in Mencenares north of Loreto, Puertecitos and coastal Sinaloa north of Mazatlán, but the largest and more distinctive Pleistocene volcanic field around the Gulf of California is El Pinacate in northwestern Sonora (see Figure 5).

El Pinacate Volcanic field has a long geological history of volcanic activity. This area contains remnants of two old arc-related volcanic episodes, which occurred in Early Miocene and Middle Miocene (23-12 Ma), respectively (Vidal-Solano *et al.* 2008). However, the most dramatic landform at El Pinacate was produced during Pleistocene time when a first episode of basaltic volcanism known as Santa Clara formed a basaltic shield volcano that progressively changed to produce felsic lavas (trachyte) from the same parent magma (Lynch *et al.* 1993). Subsequently hundreds of basaltic cinder cones, spatter cones and maar craters have formed over the last million year. Radiometric ages reported by Lynch (1981) and Slate *et al.* (1991) of several cinder cones indicates that they are probably all less than about 400,000 years old. Due to its low-K these lavas are challenging to date; nevertheless, using improved radiometric methods Gutmann *et al.* (2000) dated Crater Elegante at 32,000 ± 6,000 years. This maar-type eruption resulted from interaction of groundwater and magma. Recently Turrin *et al.* (2008) reported some of the youngest lavas flows of Pinacate at ~13 thousand years.

The source of magma for El Pinacate volcanic field is beneath the continental crust in the mantle. The geochemical and isotopic studies demonstrate that magma originated from partial melting of the peridotitic mantle beneath a thinned continental crust (Lynch *et al.* 1993) with almost no assimilation of continental material during the magma ascent, a process that is clearly related to the current phase of oblique rifting in the Gulf of California.

8. FINAL REMARKS

A large portion of the continental crust serving as substratum that supports biocycles was generated prior to the Late Cenozoic rifting episode, but most of the topographic relief over the Gulf Extensional Province was produced by Cenozoic extension of the continental crust that culminated with the rupture of the continental lithosphere along the Gulf of California in the last four million years. However, both marine and terrestrial Late Pleistocene to Holocene ecological systems around the Gulf of California developed over an active rift system that records more than 12 Ma of tectonic, sedimentary and magmatic history. The new seaway was formed, and large land-masses like Ángel de la Guarda and Tiburón islands were separated from the Peninsula and the continent, respectively, due to tectonic activity mostly along major strike-slip faults. Other islands were formed during volcanic eruptions related to the same rifting process. All these geological events have influenced the evolution of species and created unique conditions to promote local endemism.

In a geologically short time, the ecological niches within the rift system were chiefly controlled by cyclic climatic changes at the millennium scale. These changes are now widely recognized in natural archives (*e.g.* lake and marine sediments, corals, tree rings, among other geological archives). However, effects of global glacial-interglacial periods over specific regions around and within the Gulf of California are still poorly understood. For instance, during the last glacial stage (~20-30 ky ago) sea level was ~120 m lower than now (c.f. Miller *et al.* 2005) and a much larger delta plain in the northern Gulf existed due to the very shallow submerged part of the delta. This scenario implies smaller marine basins and broader coastal plains, and probably smaller fluvial discharges into the Gulf of California during glacial periods.

Another important aspect is the magnitude of displacement of climatic belts southward during the last glacial stage, and the likely increase of aridity of the circum Gulf region. Nevertheless details of how different regions onshore and offshore respond to climatic cycles are needed to understand how species and ecological niches respond to this climatic stress, and what regions received less moisture during colder conditions under expanded ice sheets at mid latitudes. High-resolution geologic archives may help to understand how species adapted to these climatic changes and what species were forced to migrate elsewhere or even disappear. The geological foundations of the Gulf of California region may explain the physiographic and lithological characteristics that support the biota, but current research in high-resolution archives will provide critical information about climatic conditions of specific regions and the ways that climatic cycles affect both the rich marine and terrestrial communities in the Gulf of California region.

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PRODUCTIVITY CHANGES IN THE MAGDALENA MARGIN OF MEXICO, BAJA CALIFORNIA PENINSULA, DURING THE PAST 50,000 YEARS

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The biological pump in the ocean plays an important role in the global carbon cycle. A substantial portion of carbon is exported and preserved on continental margins, areas that support 10 to 15% of the total production of chlorophyll across the ocean with a contribution of more than 40% of the global organic carbon export to the ocean floor. Reconstruction of past primary productivity (PP) in areas of high biological activity is important to understand how climate change affects the global carbon cycle in different timescales. Burial rates of organic carbon (Corg) and biogenic opal (BSi) were measured in a core couplet GC31/PC08 from the Magdalena margin, SW of the Peninsula of Baja California, in order to estimate changes in PP during the last 50,000 years. During the late Holocene (period between 3,000 years ago and today), the burial rate of BSi and Corg was lower than in the marine isotope stages 2 and 3 (occurred in the periods 29,000 to 14,000 and 57,000 to 29,000 years ago, respectively), including the last glacial maximum (27,000 to 18,000 years ago), suggesting that PP was greater in the latter two stages than in the most recent part of the record. In the marine isotope stage 3, the burial rate of BSi and Corg showed important oscillations coupled with DO cycles (rapid climate fluctuations that occurred in Greenland during the last glacial period with a quasi-periodically recurrence time of 1,470 years) indicating that PP in the region responds to millennial-scale global climate forcing. Our study in Baja California suggests that, in coherence with evidences from other sites along the northeast Pacific margin, the variability of the Oxygen Minimum Zone (OMZ) in the northeast Pacific is more largely controlled by changes in productivity rather than by ventilation changes of the water column, as it was the prevalent view.

Keywords: oceanic paleoproductivity, paleoclimate, global climate change, carbon export, carbon-silica burial rates, millennial cycles, marine isotope stages.

1. INTRODUCTION

The continental margin of the Baja California Peninsula is one of the four areas of the world characterized by high biological productivity in the surface and an underlying oxygen minimum zone. Along the southwestern coast of the Peninsula, upwelling intensity is greatest from April to June, changing with the local wind conditions and sea bottom topography (Zaitzev *et al.* 2003). Coastal upwelling along the west coast of Baja California changes the local properties of surface water by decreasing its temperature, enriching the water column with nutrients and hence increasing biological productivity.

The intensity of the oxygen minimum zone (OMZ) along the eastern border of the North Pacific is a function of two primary variables: 1. Ocean circulation and 2. Oxygen consumption (Wyrtki 1962). Ventilation is the process that transfers surface conditions (high oxygen concentrations) to subsurface waters (*e.g.*, by ocean circulation) (Van Scoy and Druffel 1993). Currently, the ventilation of the OMZ in the northeastern Pacific reflects the balance between the contribution of North Pacific Intermediate Water (NPIW, relatively rich in oxygen from the northern Pacific) and the Subtropical Subsurface Water (SSW, deficient in oxygen, from the southern Pacific). A relative change in the input and/or concentration of oxygen in some of these water bodies influences the intensity of the OMZ. Additionally, oxygen consumption occurs throughout the water column by oxidation of organic matter and after its deposition on the ocean floor. The higher the rate of export of labile (easy to decompose) organic matter from surface waters, the greater the deficiency of oxygen in the underlying intermediate water. In the northeastern Pacific, large changes in primary productivity occurred in the past which may have had a substantial impact on the intensity of the OMZ (Ganeshram and Pedersen 1998). Growing evidence suggest that there have been different oxygenation conditions in the past along the northeastern Pacific continental margins (*e.g.*, California and Baja California; Cannariato and Kenneth 1999, Cannariato *et al.* 1999, Stott *et al.* 1999, Ortiz *et al.* 2004, Hendy *et al.* 2004, Hendy and Pedersen 2005, McKay *et al.* 2005, Dean *et al.* 2006, Hendy and Pedersen 2006, Sánchez and Carriquiry 2007a, b, Nederbragt *et al.* 2008). These studies concluded that subsurface ventilation and/or upwelling and export production, and concomitantly the local and regional primary production, varied markedly along the northeastern Pacific continental margins during the Quaternary (the period between 2.6 million years ago and the present).

Based on the $\delta^{13}C$ isotopic gradient of benthic foraminifera that live at different depths in the sediment, Stott *et al.* (2000) estimated a decrease in the rate of oxidation of organic carbon equivalent to an increase in dissolved oxygen content of 15-20 µm/kg. This coincided with a change in the regime shift of the Pacific Ocean that occurred during 1976/1977, which involved a reduction in the number of upwelling events and an increase in ocean surface temperature by 1.5-3.0ºC. Thus, it is not necessary to invoke changes in ocean circulation and ventilation to explain changes in the OMZ of the northeastern Pacific. As a result, the new paleoceanographic evidences suggest that decreases in primary productivity caused by a deepening of the nutricline caused changes in the OMZ producing oceanographic conditions that were similar to El Niño (Ortiz *et al.* 2004). Measurements of organic carbon and trace metal concentration (Cd, Mo) in two cores from the Magdalena margin revealed millennial scale oscillations very similar to those observed in Greenland ice cores (Ortiz *et al.* 2004, Dean *et al.* 2006). This evidence convincingly suggests the operations at millennial timescale of teleconnections between the global climate and the intensity of the OMZ and/or productivity along the west coast of North America.

Recently, Schmittner *et al.* (2007) proposed that the variation of the OMZ in the Pacific Ocean can be explained by changes in the formation/subduction rates of the North Atlantic Deep Water. Through the ocean conveyor system, when the North Atlantic becomes too cold (*e.g.*, glacial conditions) there is a reduced nutrient release to the Pacific Ocean's surface resulting in decreases in primary productivity with a concomitant reduction in the exported productivity. Since there is less organic matter to be oxidized during these periods, subsurface oxygen levels in the water column start increasing concomitantly. Water column denitrification also decreases accordingly because of the increased levels of oxygen. The effect of reduced consumption of oxygen caused by lowered exported productivity at millennial timescales dominates at low latitudes.

Despite the large amount of high quality data that have been generated along the northeastern margin of the Pacific, the relative importance of surface productivity on the changes of oxygen content of intermediate water masses has not been completely assessed. For instance, the climatic event of the Bolling/Allerød (B/A, a warm and moist interstadial period that occurred during the final stages of the last glacial period, from c. 14,700 to 12,700 years before the present) was either weak and/or very intense in some places, depending on the proxies used. Moreover, the nature of the teleconnections between millennial cycles in Greenland and processes controlling the biogeochemistry and circulation over the northeastern Pacific continental margin remains a large area of debate. This study presents new data from biogenic opal of a sediment core composite GC31/PC08 collected from the southwestern margin of Baja California, where previous work has shown millennial scale fluctuations in climate over the last 50,000 years (Ortiz *et al.* 2004, Dean *et al.* 2006, Marchitto *et al.* 2007, Sánchez and Carriquiry 2007a, b).

1.1. Sedimentary proxies for reconstructing export productivity changes

Two proxies used as indicators of primary productivity are presented in this paper. The first is the accumulation rate of Corg in the sediment. The sediments in productive ocean regions usually contain high concentrations of Corg (Berger 1989). Less clear is the quantitative relationship between Corg content of the sediment and the amount of exported carbon from the ocean's surface. This is because only a small fraction of Corg produced in the surface water reaches the sediment (Suess 1980). The decomposition of Corg is affected by a number of factors, including the rate of oxidation occurred in the water column during its travel to the seafloor, the burial rate of that exported carbon that reaches the seafloor, and under certain conditions the oxygen content of bottom waters and the penetration of oxygen in interstitial water (Hedges and Keil 1995, Hartnett *et al.* 1998, Sott *et al.* 2000, Holsten *et al.* 2004). The Corg that is preserved in the sediment is usually the most refractory component of the particle flux of planktonic organic matter (Canfield 1994, Hedges and Kiel 1995) which weakens the quantitative connection to the primary productivity existing at the sea surface.

Other factors that complicate the interpretation of buried Corg are that fine sediments are typically richer in organic matter than the coarser sediments (Hedges and Kiel 1995, Nederbragt *et al.* 2008). Thus, variations in the content of Corg may be the result of changes in the source of the particles due to changes in bottom currents (Berger *et al.* 2004) or by hauling minerals (Nederbragt *et al.* 2008). Because of the larger surface-to-volume ratio of fine-grained sediments and clay minerals that tend to absorb more organic matter than coarse sediments, a wrong interpretation could be reached with regard Corg fluxes to the ocean's floor. Hence, when grain size differences are suspected to exist in a sedimentary record, a grain-size normalization is commonly performed to achieve the correct interpretation.

The other proxy for primary productivity is the content of biogenic opal (BSi) in the sediments, which is commonly associated with oceanic regions characterized by high primary productivity resulting from upwelling systems with high deposition and preservation (*e.g.*, burial) rates of BSi (*e.g.*, Sánchez and Carriquiry 2007a). Because the ocean is undersaturated with respect to silicic acid, the BSi is dissolved in its path along the water column to the sediment-water interface. A small residual fraction of settling BSi escapes dissolution. Oceanic sites with sediments rich in BSi are clearly related to regions with high surface production of BSi that also have the tendency of supporting blooms of diatoms, especially dominated by the large and robustly silicified species (*e.g.*, Calvert and Price 1983, Nelson *et al.* 1995, Pondaven *et al.* 2000, Ragueneau *et al.* 2000). In fact, BSi is one of the most widely used proxies in reconstructions of paleoproductivity and in conjunction with other proxies such as Corg, this multiproxy approach can give a consistent scenario of past changes in export productivity (*e.g.*, Hendy *et al.* 2004, Hendy and Pedersen 2005, McKay *et al.* 2005, Sánchez and Carriquiry 2007a, Nederbragt *et al.* 2008).

2. MATERIALS AND METHODS

The sediment cores (GC31 and PC08) of this study were collected from the open slope of the northeastern Mexican Pacific (see Figure 1), within the OMZ, also known as the Magdalena margin (Ortiz *et al.* 2004). Two complementary cores, a gravity (GC31) and a piston (PC08) core, were raised from a depth of 700 m, at 23°28' N and 111°36' W. The combined length of both cores was ~15 m. Oxygen concentration at the site was <3 mmol kg^{-1} (clearly suboxic). The sedimentation rate at the site of GC31/PC08 was assessed from 52 individual ^{14}C datings of planktonic and benthic foraminifera (van Geen *et al.* 2003, Marchitto *et al.* 2007), and 21 tie-points were established with the Hulu Cave record that was ^{230}Th-dated (Wang *et al.* 2001, Marchitto *et al.* 2007). The calculated sedimentation rate in this site was determined to be ~30 cm ka^{-1} (Van Geen *et al.* 2003). The cores were sampled every 5 cm (resolution ~170 years); each sample had a thickness of 1 cm, which integrated ~30 years.

2.1. Biogenic components

2.1.1. Total organic carbon (C_{org})

C_{org} as content of sediment was determined using a LECO elemental analyzer. Prior to analysis, carbonates were removed from the sample by acid treatment with 10% HCl. C_{org} content was estimated as weight percent. The analytical precision of elemental C content was <0.5%.

2.1.2. Biogenic opal (BSi)

The content of biogenic opal (BSi) in sediment was analyzed by the alkaline extraction method (Mortlock and Froelich 1989). The silica is measured after dilution of the samples using the 'molybdate blue' spectrophotometric method (Strickland and Parsons 1972). Some samples were analyzed in duplicate, yielding an analytical precision of this extraction method of <2%. The obtained concentration of dissolved silica is later converted to BSi and expressed as percentage by weight.

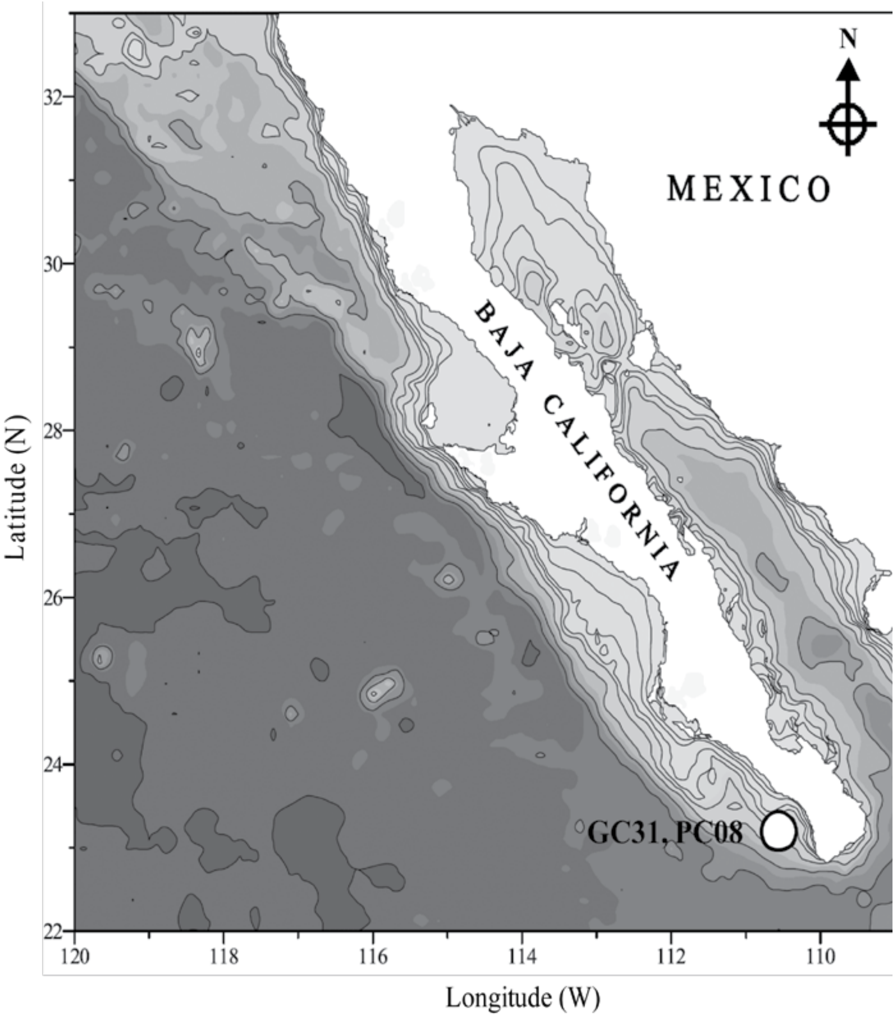

FIGURE 1. Bathymetric map and location of sediment cores GC31/PC08 in the Magdalena margin, Baja California Sur, Mexico.

2.1.3. Accumulation rate

Accumulation rates (AR) for biogenic components were calculated from the density of dry sediment taken from Dean *et al.* (2006). The sedimentation rate (cm ky^{-1}) and the percentages of biogenic components were multiplied by the density of dry sediment to estimate the accumulation rates (mg cm^{-2} ky^{-1}) for each biogenic component. Because the sedimentation rate's slope is practically a straight line, the assumed constant sedimentation rate in this site is very realistic (Ortiz *et al.* 2004).

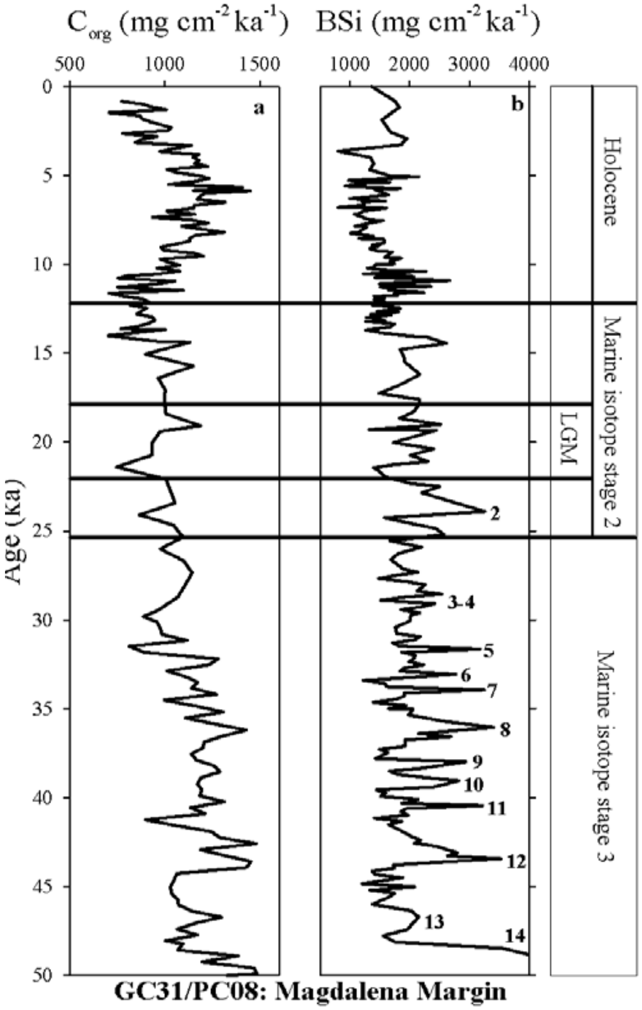

FIGURE 2. Burial rate of (a) Corg (mg cm-2 ka-1) and of (b) BSi (mg cm-2 ka-1) in the Magdalena margin, at 700 m depth. Labels in the diagram (b) indicate interstadial events 2–14.

3. RESULTS

3.1. Sedimentation rate of C_{org} and BSi

C_{org} flux in the cores GC31-PC08 from Magdalena margin displays high variability (500 to 1500 mg cm^{-2} ky^{-1}) during the last 50 Ka (see Figure 2a). Average C_{org} flux during the Holocene was from 1062 ± 155 mg cm^{-2} $ky^{-1}$and decreased to 700 mg cm^{-2} ky^{-1}during the late Holocene (see Figure 2a). During the marine isotope stage

2 (MIS-2), the C_{org} flux was slightly lower (932 ± 120 mg cm^{-2} ky^{-1}) but similar to the last glacial maximum (22-18 ky) (963 ± 143 mg cm^{-2} ky^{-1}). C_{org} flux during the MIS-3 was slightly higher (1150 ± 159 mg cm^{-2} ky^{-1}. In general, it can be said that the C_{org} burial rate was relatively higher during the warm periods than during the cold periods of the MIS-3 (see Figure 2a).

The BSi sedimentation rate, like the C_{org}, displayed considerable variability during the last 50 Ka (see Figure 2b). During the MIS-3, there were several events of maximum levels of BSi concentration, balanced by a similar number of events containing minimum levels of BSi. During the Holocene, the average BSi flux was 1475 ± 352 mg cm^{-2} ky^{-1}. During the MIS-2, the average BSi flux was 1828 ± 404 mg cm^{-2} ky^{-1} and particularly during the LGM, the average BSi was 1908 ± 413 mg cm^{-2} ky^{-1}. BSi values in the period of 50 to 25 Ka (MIS-3) showed a range very similar to the DO cycles recorded in the Greenland's ice core record.

4. DISCUSSION AND CONCLUSIONS

The comparison of the different components: C_{org}, BSi, abundance of benthic foraminifera and the DSR-factor 3 (the latter two from Ortiz *et al.* 2004) in the GC31/PC08 cores respond in time and magnitude (except C_{org}) to $\delta^{18}O$ variations in the GISP2 ice core (see Figure 3). The sedimentation rate of C_{org} during some intervals during the MIS-3 had limited response to millennial-scale 'DO' oscillations (see Figure 3c). The rate of burial of C_{org} in the Magdalena margin during the Holocene was 1062 ± 155 mg cm^{-2} yr^{-1}, which is similar to the modern C_{org} flux in Soledad basin (824 mg cm^{-2} yr^{-1}). During the warmer periods of the MIS-3, the average burial rate of C_{org} was 25% higher, reaching the maximum value of 1450 mg cm^{-2} yr^{-1} which is similar to the maximum values observed during the Holocene. During the cold periods of the MIS-3, the average burial rate of C_{org} was slightly lower than that of the Holocene. The MIS-2 and LGM, periods of similar conditions to the cold events of the MIS-3, presented C_{org} burial rates in the order of 932 ± 120 mg cm^{-2} yr^{-1}, and 963 ± 143 mg cm^{-2} yr^{-1}, respectively. These C_{org} fluxes were very similar to the Holocene's, but significantly lower than those of the warm events of the MIS-3.

BSi flux calculations agree well with the C_{org} comparisons between periods of contrasting climatic conditions during the last 50,000 yrs. Particularly for the MIS-3, the burial rate of BSi fluctuates in synchrony with the millennial scale climate oscillations observed in the $\delta^{18}O$ of the Greenland ice core (GISP2). These new observations suggest that fluctuations in the intensity of the OMZ in the northeastern tropical Pacific were caused by changes in productivity and, by a lesser degree, by the formation of the NPIW (North Pacific Intermediate Water which implies

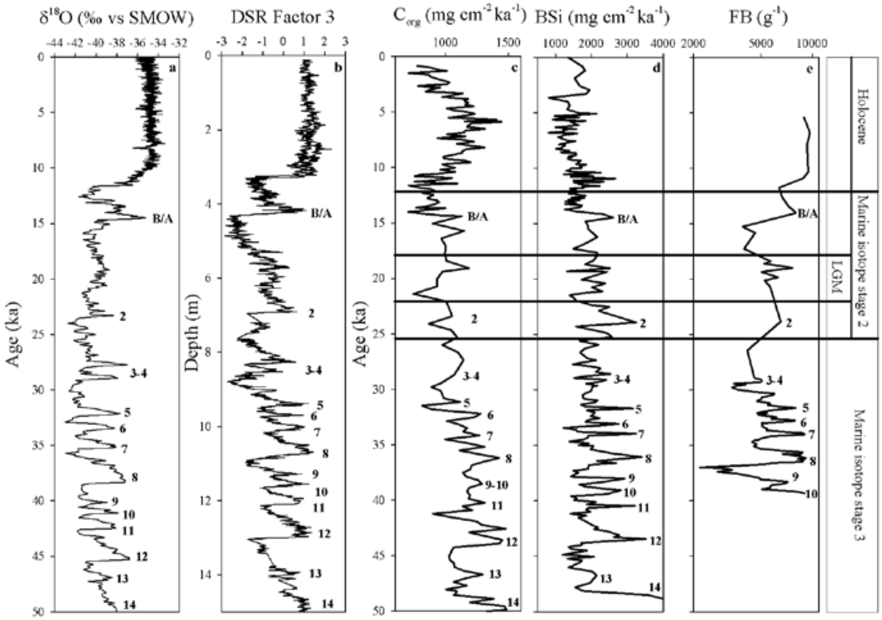

FIGURE 3. (a) d18O of the Greenland ice core (GISP2; Grootes and Stuiver, 1997), (b) of DSR-Factor 3 (Ortiz *et al.*, 2004), (c) burial rate of Corg (mg cm-2 ka-1), (d) BSi (mg cm-2 ka-1) and (e) flow of benthic foraminifera (Ortiz *et al.*, 2004) in the Magdalena margin, at 700 m depth. Numeric labels in the diagrams correspond to interstadial events 2–14.

"renewed" ventilation). This is in agreement with recent evidence that these millennial-scale events of high productivity should produce a more pronounced OMZ, which is more oxygen deficient, as will be further discussed.

The preservation of sedimentary C_{org} is an empirical relationship that is related to primary productivity, C_{org} flux along the water column, sedimentation rate, the rate of degradation of C_{org} and the background concentration of oxygen in the water column. The mechanisms that control the sedimentary organic carbon preservation remain unclear and continues to be debated (*e.g.*, Hartnett *et al.* 1998, Hendy *et al.* 2004, McKay *et al.* 2005, Sánchez and Carriquiry 2007a, Nederbragt *et al.* 2008).

What factors may facilitate an increase in the rate of burial of C_{org} during the warmer periods of the MIS-3? The very well dated core couplet GC31/PC08 allowed for precise determinations of sedimentation rate in the Magdalena margin. The sedimentation rate for the Holocene, the MIS-2 and LGM was 30 cm ky^{-1} (0.30 mm yr^{-1}), and slightly decreased to 25 cm ky^{-1} during the MIS-3 (0.25 mm yr^{-1}). The similarity in the sedimentation rate suggests that there is no artifact introduced by sedimentation rate and that the accumulation rate of C_{org} was the result of changes in primary productivity and C_{org} flux along the water column (*e.g.*, Hedges and Keil 1995, Hartnett *et al.* 1998).

Hartnett *et al.* (1998) suggest that the burial and preservation of C_{org} in the continental margin is mainly related to the oxygen's exposure time (estimated to be 3 months), considering that the oxygen's penetration depth (into the sediment; see Hartnett *et al.* 1998 for details) is very shallow (<2 mm). In the margin of Magdalena, the oxygen exposure time was 45 days (with <2 mm) and an oxygen penetration depth of <1 mm; the calculated time is very similar to Hartnett's *et al.* (1998). Thus, the exposure time to oxygen explains very little in terms of preservation and accumulation of C_{org} in the Magdalena margin. Canfield (1994) suggested that the efficiency of C_{org} burial decreases with increases in primary productivity, and the rain of C_{org} due to the mixing of labile and refractory C_{org} that increases the oxidation of C_{org}. Indeed, Berelson and Stott (2003) found that the efficiency of C_{org} burial for the past 100 years was lower than in the present in the central California margin, and concluded that the burial of C_{org} efficiency was not related to the exposure time to oxygen.

Recently, the age distribution of the settling particles and their exposure time to oxygen in bioturbated marine sediments was modeled for the continental shelf and slope. The results indicated that the biodifusive mixture of particles and the preferential degradation of organic matter under conditions of oxygenation predicts an inverse relationship between the burial efficiency and the exposure time to oxygen in marine sediments, and differs from a simple relationship between oxygen penetration and the rate of sedimentation (Meile and Van Cappellen 2005).

Under the current scenario, the concentration of oxygen in the OMZ depends on the balance between the relative contribution of the intermediate waters from the "North Pacific subsurface water' which is relatively rich in oxygen, and the oxygen-poor 'subsurface waters of the equatorial Pacific". Thus, any change in the mixing contributions of the two sources would directly impact the condition of the OMZ of the northeastern Pacific. The North Pacific intermediate water (NPIW) that is formed in the Okhostk Sea and the Gulf of Alaska (You 2003, Shcherbina *et al.* 2003), and travels along the North Pacific subtropical gyre, was suggested to explain the ventilation of the water column and the presence of bioturbated intervals during cold periods or stadials (LGM, and the stadials of the MIS-3) along the northeastern Pacific and Gulf of California. In contraposition, laminated sediments formed during the Holocene and the interstadials of the MIS-3, indicating low oxygen levels in the water column (Duplessy *et al.* 1988, Keigwin and Jones 1990, Kennett and

Ingram 1995, Van Geen *et al.* 1996, Behl and Kennett 1996, Keigwin 1998, Zheng *et al.* 2000).

Better ventilation in the northeastern Pacific during the last glacial has been inferred from the $\delta^{13}C$ values of benthic foraminifera that suggest the presence of a "young" intermediate water mass in the northwestern Pacific, low in nutrients (Duplessy *et al.* 1988, Keigwin 1998, Stott *et al.* 1999, Keigwin 2002). ^{14}C data on benthic and planktonic foraminifera in sediment cores from the west Pacific suggest an increase in ventilation between 17 and 13 ka, and during the Younger Dryas, as well as a decrease in ventilation during the Bolling/Allerød (Duplessy *et al.* 1989). Nonetheless, Keigwin (2002) indicate similar ventilation conditions during the Holocene and last glacial maximum and suggests that the possible source of ventilation was the Gulf of Alaska, or the Southern Ocean. In Santa Barbara Basin, ventilation increased during the last glacial maximum and the Younger Dryas (this event was a brief period of cold climatic conditions and drought that occurred between approximately 12.8 and 11.5 Ka ago) (Ingram and Kennett 1995), which contrasts with data from the open California margin that show, ambiguously, a decrease in ventilation between 11 and 9 Ka (Van Geen *et al.* 1996), and increased ventilation in the early Holocene (11-8 ka) and Bolling/Allerod, while the OMZ was intensifying (Mix *et al.* 1999). In fact, McKay *et al.* (2005) shows that ventilation in the water column, compared to Vancouver Island for the period between 16 and 12.6 Ka (including the B/A) was very similar to the present.

Age differences between benthic-planktonic foraminifera used to infer changes in ventilation have the limitations that it considers a constant reservoir age of surface water and plankton. However, the concentration of atmospheric ^{14}C, the ocean-atmosphere exchange, and the changes in the circulation may influence the reservoir age estimate, as the diagenesis of methane influences the $\Delta^{14}C$ and ^{13}C (*e.g.*, Keigwin, 2002). Overall, the collected evidences from countless sedimentary records seem to indicate that the ventilation of the water column remained unchanged over the last 25 ka, and the observed changes in the OMZ of the Northeast Pacific are therefore caused by changes in primary productivity and not ventilation.

The high productivity in the Pacific NW is suggested as a new driving mechanism for the low levels of O_2 observed at intermediate depths along the western margin of North America. Near the site of NPIW formation, O_2 consumption took place by an increase in respiration of C_{org} in response to the high productivity of the period from 14.7 to 12.9 Ka (Crusius *et al.* 2004). Off Vancouver Island, C_{org} fluxes were significantly higher, relative to the Holocene, suggesting the activation of an upwelling system as the atmospheric and oceanic circulation was restored from a glacial to interglacial mode (McKay *et al.* 2005). Thus, the consumption of oxygen by high productivity on the sites of formation of North Pacific intermediate water, in these time-intervals, suggest the presence of the NPIW poor in oxygen and not due to decreased ventilation at intermediate depths, which is supported by ^{14}C estimates. In fact, Galbraith *et al.* (2007) indicate a rapid acceleration of export production during the deglaciation (18-15 ka) in the Pacific Northwest derived from an increased supply of nutrients, leading to increased sequestration of CO_2 at intermediate depths.

The sedimentary record of Santa Barbara Basin shows alternation of laminated and bioturbated sediments that have been associated with changes in the oxygenation of the water column and sediment, as well as on the presence/absence of benthic foraminifera species (*e.g.*, Cannariato *et al.* 1999). Nederbragt *et al.* (2008) show high burial rates of C_{org} under both, oxic conditions (>2 ml l^{-1} O_2) (*e.g.*, Younger Dryas) and dysoxic conditions (2 to 0.2 ml l^{-1} O_2) (laminated sediments). These results support the evidence of the oxygen level control by variation in the intermediate water ventilation, and not by changes in productivity in surface waters in this basin.

Mix *et al.* (1999) suggest that the Southern Ocean may be an important source of variability in the North Pacific. The expansion of the OMZ in the Gulf of California precedes the expansion occurring in the California margin during the deglaciation, but coincides with changes in ice cover and winds around Antarctica. These observations reinforce the importance of Southern Ocean as a primary modulator of climate in the Northern Hemisphere (Hendy *et al.* 2004). Marchitto *et al.* (2007) reconstructed the activity of ^{14}C at intermediate depth in the northeast Pacific, finding that this activity decreased sharply during the deglaciation, suggesting the arrival of a very old water mass originating in the Southern Ocean. Thunell and Kepple (2004) indicate that denitrification of the water column in the Gulf of Tehuantepec is sensitive to changes in ventilation and circulation in the subsurface water of oxygen deficient as well as variations in the intensity of upwelling (*i.e.*, marine productivity).

Besides Santa Barbara Basin, the northeastern Pacific sedimentary records that extend into the marine isotope stage 3, with millennial or sub-millennial resolution are very scarce. Hendy *et al.* (2004) followed a multiproxy approach in a sediment core collected from the active upwelling cell of Point Conception, California. The results suggest that marine productivity in this region was not simply linear between warm and cold climatic oscillations (*e.g.*, glacial - interglacial), except for the marine isotope stage 3 where the upwelling cell and the resulting productivity remained active during warm events (interstadials) and inactive during cold events (stadials). Productivity increased dramatically during the Bolling warming interval, while in the Allerød and Younger Dryas were much less productive. The response of productivity resulted from a complex interaction of local winds and a more vigorous subsurface flow. Thus, export production and ventilation of intermediate water played an important role in the development of California margin OMZ (Hendy and Pedersen 2005).

Low latitude paleoproductivity records from the northeast Pacific margin are restricted to the subtropical latitude of the Gulf of California, with a time scale limited to the last 25 ka, and the open margin of Magdalena with a timeline that extends to 50 ka, consisting of millennial and sub-millennial resolution. Ortiz *et al.* (2004) suggest that productivity changes recorded in the Magdalena margin during MIS-3 were balanced similarly to the modern conditions of La Niña that favored a shallow nutricline and consequently high productivity during warm climate intervals alternating with El Niño-like conditions, with a deep nutricline and low productivity intervals during cold periods. The concentrations of C_{org}, cadmium and molybdenum were measured in the same core studied by Dean *et al.* (2006). The accumulation of C_{org}, Cd and Mo generally corresponded to warm periods with the exception of B/A, which is weakly expressed on the Baja California margin. The new data provide evidence of teleconnections between global climate and the intensity of the OMZ and/or productivity along the northeastern Pacific margin.

The sedimentary record of Pacific and Indian oceans documenting millennial scale fluctuations in dissolved oxygen levels and denitrification are consistent with the oscillation of temperature in the North Atlantic. Schmittner *et al.* (2007) have recently modeled the oxygen and nitrogen cycles explaining how the changes in subduction of deepwater in the North Atlantic can cause the synchronic variations in the OMZ of the Pacific and Indian Ocean. Cold periods in the North Atlantic are associated with reduced nutrients release to the surface of the Pacific and Indian Oceans. As a result, export production decreased and the subsurface respiration of organic matter was reduced leading to an increase in the concentration of oxygen and less denitrification at lower latitudes.

Generally, the flux of BSi in the range of Magdalena indicate that during some marine isotope stages, as is the case of MIS-3, primary productivity associated with diatoms (mainly) fluctuated in synchrony with the 'D-O' cycles in Greenland. Our study in Baja California suggests that, in coherence with evidences from other sites along the northeast Pacific margin, the variability of the Oxygen Minimum Zone (OMZ) in the northeast Pacific is more largely controlled by changes in productivity rather than by ventilation changes of the water column, as it was the prevalent view. The low C_{org} preservation during some millennial-scale events would suggest a decrease in productivity and/or increase of ventilation of the water column, which contrasts with the increase in the flux of BSi and in the abundance of benthic foraminifera. Ocean circulation changes responsible for increasing the oxygen content of the water column is the most likely controlling factor explaining the divergence of the paleoproductivity proxies during these events.

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NUMERICAL MODELING OF THE CIRCULATION OF THE GULF OF CALIFORNIA: A BRIEF HISTORY

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A brief history of the numerical modeling of the circulation of the Gulf of California (GC) is presented. It started from homogeneous models in one- and two-dimensions studying the tidal propagation along the Gulf, tidal dissipation, generation of residual currents and the wind-induced currents. More complete inhomogeneous models followed, also in a one-, two- and three-dimensions fashion. Obviously, details of the circulation with the latter models were better modeled but also new findings came. Understanding sometimes the physics of observations or measurements, which includes the reality with all time and spatial scales unfiltered, is difficult. The actual state of the art of the models of the GC are close to be functional (not operational yet) and will be a useful tool to understand both the dynamics of the Gulf and, combined with biological models, the behavior of some fisheries which would allow the decision makers to properly manage some important fisheries of the Gulf.

1. INTRODUCTION

The physical oceanography of the Gulf of California (GC) has been studied since the early 1940's. Observations from ships, instrumental arrays, satellite measurements and numerical modeling have advanced the understanding on how its general circulation is driven and a comprehensive review of the actual knowledge can be consulted in Lavín and Marinone (2003). Briefly, "the engine" behind the Gulf's circulation is the result of the combined forcing of the Pacific Ocean (PO) through its opening, the atmospheric forcing/interaction over its entire surface, and the local stirring induced by bathymetric features such as sills, capes and basins. Obviously, this large spectrum produces several features which interact and produces many structures with a broad band of spatial and temporal scales. However, the time scales from hours (due to tides) to seasonal (due to the earth's journey around the sun) are pretty well studied.

Due to the large communication with the PO, the water masses of the Gulf are the same as the adjacent ocean, namely, Pacific Deep, Pacific Intermediate, Subtropical Subsurface, California Current, Tropical Surface, plus the Gulf of California Water (GCW), locally produced in the northern Gulf (Bray and Robles 1991). Another particular feature of the Gulf, related to the production of the GCW, is that the Gulf is an evaporative basin that gains heat in the annual average.

Also, because of the direct communication with the PO, features such as currents, coastal trapped waves, tides and El Niño signals, freely enter the Gulf and dominate the Gulf's circulation, especially at the seasonal scale (Ripa 1997). The seasonal surface circulation induced by the PO is in phase with that produced by the monsoonal winds over the surface resulting in a summer cyclonic and winter anticyclonic circulation. The tides of the Gulf are in co-oscillation with the PO and the semidiurnal components are near resonance resulting in a four fold increase in amplitude at the head of the Gulf. The associated tidal currents increase accordingly and especially at the midriff islands area where extensive mixing occurs (Paden *et al.* 1991). This intense mixing over the sills, interpreted as tidal pumping, dominates the mean and low frequency deep circulation (López *et al.* 2006, 2008) around Ángel de la Guarda Island. Many mesoscale features are produced by local processes that interact with this seasonal circulation and produce structures such as plumes, jets, fronts, gravity currents, etc., which still needs to be studied.

In this chapter, a brief chronological story of the numerical modeling studies of the Gulf's circulation is presented. Some of these models have focus on known features of the Gulf circulation and dynamics; others have resulted in key contributions to the present knowledge of the physical oceanography of the Gulf. As there are many numerical models adapted to the Gulf, here they are presented in three groups as follows: Section 2 and 3 are devoted to homogeneous (barotropic) and inhomogeneous (baroclinic) models, respectively, adapted to or developed for the GC. Section 4 presents global models that have zoom into the Gulf. Within each group, the models are presented almost in chronologically order and Tables 1, 2 and 3 present (almost) all of them, with their forcing, some basic characteristics and the main topic modeled/studied. There will be no critical analyses about the validation of their results, for that the reader should consult the original papers; only the achieved goal is highlighted and taken as valid. Finally, in Section 5 different applications with interdisciplinary focus are presented.

2. HOMOGENEOUS MODELS: ONE-, TWO-, AND THREE-DIMENSIONAL

Homogeneous models were initially devoted to study the tides in the Gulf with both, one- and two-dimensional models (see Table 1). The first numerical model was the two-dimensional (2D) model of Grijalva (1972), who reproduced the general behavior of the M2 tidal constituent, *i.e.*, the propagation of the tide around the Gulf with its amplification due to resonance. His model included a non linear parameterization of the friction term but excluded advection. Stock and Filloux (1975) and Stock (1976) followed with both one-dimensional (1D) linear model and a 2D model including also non linear friction only. He made the first calculations of the energy dissipation from a numerical model (Filloux 1973, calculated the tidal energy dissipation from few observations before) due to the tides and studied the resonance behavior of the different tidal constituents.

As mentioned before, the semidiurnal band is close to resonance. A direct consequence of this amplification is the large tidal currents that are produced, and their interaction with topography leads to tidal rectification (Zimmerman 1978), that is, the generation of mean or residual currents. Quirós *et al.* (1992) first modeled the residual currents produced by the M2 component with the use of a full nonlinear model. Only over the shallow northern Gulf and in the midriff archipelago, the currents were found significant.

Two more one-dimensional models followed (De León and Ripa 1989, Ripa and Velázquez 1993) with the intention to model the general behavior of the tides along the Gulf exploiting the fact that they are simpler and faster than the 2D models (in a computational sense) to explore, for example, the dependence of dissipation with different parameters. But, with the development of more powerful computers, the two- and three-dimensional (3D) models were pursued as they give much more detailed information.

In the second half of the 1990s several two- and three-dimensional models were reported (see Table 1). All of them were fully nonlinear and focused on the residual flow (tidal rectification) generation with one or many tidal constituents and more calculations of tidal energy dissipation. Tidal rectification was known to be important in the northern Gulf and at the islands area, where also more energy dissipation happens. Marinone (1997) found that the residual currents are mainly produced by the M2 tidal constituent, difficult to 'see' from observations only. The effect of the wind and topographic stress on the residual circulation was studied by Argote *et al.* (1998) and Marinone (1998) (see also Salas de León *et al.* 2003, and Makarov and

TABLE 1. One-, two- and three-dimensional homogeneous models. These models were only forced by tides and winds. In the forcing column W stands for wind, and M2, N2, K1, O1 are tidal constituents. MTC mean that more than the previous 4 tidal constituents were included. L and FNL stands for linear and fully nonlinear, respectively, and NA for not available.

Numerical study	Forcing	Characteristics	Resolution	Modeled
Grijalva (1972)	M2	2D, non-linear friction	7×7 km	Elevation and tidal currents - First model
Stock and Filloux (1975)	M2	1D, L	NA	Energy flow and dissipation
Stock (1976)	M2, S2, N2, K1	2D, non-linear friction	10×10 & 20×20 km	Energy dissipation, resonance character, shape of the 'modeled' Gulf
Quirós *et al.* (1992)	M2	2D, FNL	7×7 km	Elevations, tidal currents and residual circulation
De León and Ripa (1989)	M2	1D, L	6.6 km	Energy dissipation, amplitudes and phases along the Gulf
Ripa and Velázquez (1993)	MTC	1D, L	6.6 km	Amplitudes and phases along the Gulf
Argote *et al.* (1995)	M2	2D, FNL	6.6×6.6 km	Elevation, tidal currents and energy dissipation
Marinone (1997)	MTC	2D, FNL	6.5×6.5 km	Mean and low frequency residual circulation, momentum and energy budgets
García-Silva and Marinone (1997)	M2	2D, FNL	14×14 to 2×2 km	Effect of grid size on mean residual circulation
Carbajal and Backhaus (1998)	MTC	2D, FNL	10.2×9.4 km	Residual current and energy budget
Marinone (1998)	M2 and W	2D, FNL	6.5×6.5 km	Effect of topographic stress on mean residual currents
Argote *et al.* (1998)	M2 and W	2D, FNL	6.6×6.6 km	Effect of tidal and wind forcing on mean residual currents
Garcia-Silva and Marinone (2000)	MTC	2D, FNL	6.5×6.5 km	Tidal dynamics and energetics

TABLE 1 (CONTINUED).

Numerical study	Forcing	Characteristics	Resolution	Modeled
Marinone (2000)	M2, S2, K1, O1	2D and 3D, FNL	6.5×6.5 & 4.6×3.9 km and 12 layers & 20 σ levels	3D modeling of tidal currents
Salas de León *et al.* (2003)	M2	3D, FNL	5.1×4.7 km, 12 layers	Effect of tidal stress on residual currents
Makarov and Jiménez-Illescas. (2003)	Potential vorticity conservation	2D, FNL	7.8×9.2 km	Stationary currents due to planetary and topographic effects

Jiménez-Illescas 2003 whom focus more on theoretical aspects such as tidal stress and potential vorticity conservation). The inclusion of the wind forcing produces stronger currents, especially along the coast at the southern half of the Gulf.

An interesting result comparing 2D and 3D modeling of the tides showed that the tidal heights are better modeled with a simple two-dimensional model, while the three-dimensional model reproduced better the tidal currents (Marinone, 2000).

Diagnostic analyses such as momentum, vorticity and energy budgets, effects of tidal stress, and combinations of the forcing are included in many of the papers (from the models) to explain different features. With these models, tidal heights and currents, the associated residual circulation, and the circulation produced with the wind forcing with the rectified tidal currents were well studied. But perhaps the most important lesson from these models was the building of knowledge as a reference towards the understanding of the general circulation which is rich in thermohaline structure, such as water masses, sea surface temperature, heat and salt fluxes, etc.

As examples of the results obtained by these homogeneous numerical models, Figure 1 shows the amplitudes of the M2 and K1 tidal constituents which are the largest of the semidiurnal and diurnal bands, respectively, and the factor form which measures the relative importance of the diurnal to semidiurnal bands. Note that the amphidromic point is shifted to the west, which is due to the energy dissipation as the tidal wave propagates around the Gulf. If there were no energy dissipation, the amphidromic point would be at the center of the Gulf. These results were recreated from the model of Marinone (2003) but were obvious since Grijalva (1972).

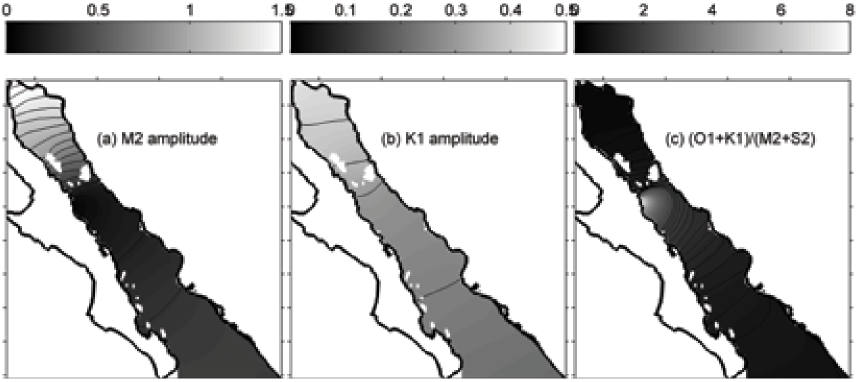

FIGURE 1. Amplitude of the largest semidiurnal and diurnal tidal (a) M2 and (b) K1, respectively, and (c) factor form calculated as the sum of the amplitudes of the K1 and O1 diurnal constituents divided by the sum of amplitudes of the M2 and S2 semidiurnal constituents.

3. INHOMOGENEOUS MODELS: ONE-, TWO-, AND THREE-DIMENSIONAL

The first three-dimensional baroclinic model was that of Carbajal (1993) (see Table 2). He studied the general circulation with a stratified Gulf but forced only with the tides and the winds. No structure of the hydrography or associated currents in the opening was included. Many results are presented in this work about the baroclinic circulation of the currents due to the M2 tidal component, winds and their combinations.

A key simple linear "one-dimensional" two-layer numerical model for the understanding of the origin of the seasonal variability of the Gulf's circulation was that of Ripa (1997). He demonstrated that most of the dynamics and thermodynamics are controlled by the PO, with the wind stress and heat fluxes playing a secondary role. No tidal forcing was included in his analyses. Beier's two-dimensional two-layer linear model followed and corroborated Ripa's result but found that the wind stress forcing is almost as important as that of the PO. This model was used also to study the seasonal evolution of the circulation and the effect of the stratification on the circulation of the northern Gulf (Beier and Ripa 1999 and Palacios-Hernández *et al.* 2002).

TABLE 2 (RIGHT). One-, two- and three-dimensional inhomogeneous models. In the forcing column W stands for wind, M2, N2, K1, O1 are tidal constituents. MTC mean that more than the previous 4 tidal constituents were included. PO, H and E mean forcing by the Pacific Ocean, heat, and evaporation, respectively. L and FNL stands for linear and fully nonlinear, respectively, and NA for not available.

Studies	Forcing	Characteristics	Resolution	Modeled
Carbajal (1993)	MTC and W	3D, FNL	10.2×9.4 km, 12 layers	Tidal currents and general circulation
Ripa (1997)	W, H, PO	L, 1D	2 layers	Relative importance of the three forcing at the annual scale
López (1997)	W, H, W	3D, FNL	6.6×6.6 km, 19 levels	Water mass formation
Beier (1997)	W, H, PO	L, 2D	6.6×6.6 km, 2 layers	Sea level and surface annual circulation, heat balance
Beier and Ripa (1999)	W, H, PO	L, 2D	6.6×6.6 km, 2 layers	Annual surface circulation, heat balance
Palacios *et al.* (2002)	W, H, PO	L, 2D	6.6×6.6 km, 2 layers	Effect of the seasonal stratification on the circulation
Marinone (2003)	MTC, W, H, E, PO	3D, FNL	3.9×4.6 km, 12 layers	Mean and seasonal circulation, SST, heat and salt balances
Martinez and Allen (2004a,b)	Meso-scale waves from PO	3D, FNL	3.0×3.0 km, 50 σ levels	Propagation of waves
Marinone and Lavín (2005)	MTC, W, H, E, PO	3D, FNL	3.9×4.6 km, 12 layers	Tidal currents ellipses
Allende (2005)	W, H, PO	3D, FNL	NA	Energetics of physical processes
Mateos *et al.* (2006)	MTC, W, H, E, PO	3D, FNL	3.9×4.6 km, 12 layers	Eddy formation
Marinone (2007)	MTC, W, H, E, PO	3D, FNL	3.9×4.6 km, 12 layers	Deep circulation at large islands area, tidal mixing
Marinone (2008)	MTC, W, H, E, PO	3D, FNL	1.3×1.5 km, 12 layers	Deep circulation at large islands area, tidal mixing
Gómez (2008)	W, H, PO, MTC	3D, FNL	E-O 3 km N-S 3.3-5.6 km 20 levels	Effect of tidal mixing on SST
Zamudio *et al.* (2008)	Nested models	3D, FNL	7.8×9.2 km, 20 z-levels	Generation of eddies during summer

The only model dealing with water mass formation in the Gulf of California is that of López (1997). Modeling only the northern Gulf with wind, surface heat flux and evaporation forcing found that water mass is formed in the shallow areas where the water cools and sinks and then follows a cyclonic circulation. The latter modeled winter circulation is in accordance with future findings with more complete models, as shown below.

Then, a combination of the previous models and forcing with a multi-layer baroclinic model by Marinone (2003) followed. The numerical model is the same as that of Carbajal (1993) but the forcing is inspired on all the knowledge mentioned before, *i.e.*, by the PO through temperature, salinity and sea level at tidal and climatological time scales and at the sea surface by climatological winds, heat and freshwater fluxes in order to model the mean and seasonal circulation. The relative importance of the different forcing to reproduce the SST and the general circulation in different regions was determined. In general, the PO and the winds largely determine the overall seasonal circulation of the Gulf but the contribution to the mean circulation by the tides was found (with a full 3D baroclinic model) to be important in the northern Gulf and islands region. Also, from this model, the tidal currents ellipses were modeled overall the Gulf (Marinone and Lavín 2005) for a broad number of tidal constituents.

The propagation of coastal trapped waves entering the Gulf was modeled by Martínez and Allen (2004a, b). They found that most of their energy, when reaching the sill area, returns through the Peninsula side and a small fraction enters the northern Gulf where it is dissipated. Bravo (2011) studied the propagation of internal tides produced by the interaction of the barotropic tide and sills at the central Gulf.

The bottom circulation around Ángel de la Guarda Island proposed by López *et al.* (2006, 2008) was modeled by Marinone (2007, 2008) after a refinement of the model of Marinone (2003) in which the horizontal resolution was reduced by a factor of three. This deep circulation is persistent along the year and explains the cold surface and nutrient rich waters of Canal de Ballenas by means of a deep convergence of the currents that leads to a semi-permanent upwelling. Also, Gómez (2008) modeled the effect of the bathymetry and the tides on the generation of cold SST of the northern Gulf.

The propagation and generation of anticyclonic eddies in the southern Gulf was modeled by Zamudio *et al.* (2008) with a series of nested models and found that they are not locally generated and are produced by the remote forcing of the Pacific, in accordance with previous models of the Gulf.

As examples of the results obtained with the inhomogeneous models, Figure 2 shows the surface seasonal circulation induced by the seasonal forcing of the PO

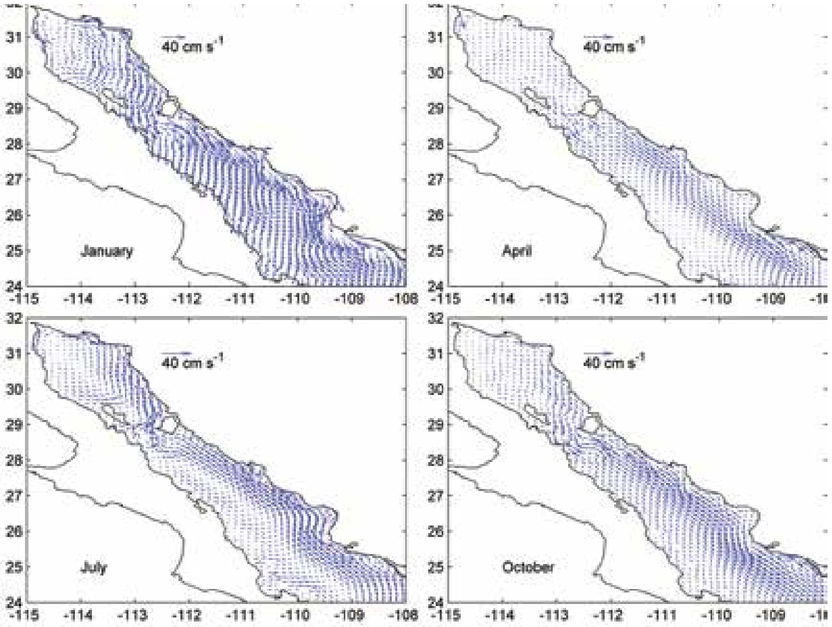

FIGURE 2. Surface seasonal circulation. The currents represent the average of the indicated month. The model was forced with tides and climatological temperature and salinity fields at the mouth, climatological heat and freshwater fluxes and winds at the sea surface. Only one every eleven vectors are plotted for clarity.

(climatologic temperature and salinity fields and the tides), wind, heat, freshwater fluxes and tides. The northern Gulf is dominated during winter by the basin wide cyclonic gyre and during summer by the anticyclonic gyre. The southern Gulf develops a strong coastal surface current at the mainland side. Figure 3 shows the bottom circulation around Ángel de la Guarda Island for February and September for the last and penultimate model layers. This circulation is persistent almost all year round. The results of Figure 2 and 3 were obtained from the model of Marinone (2008).

4. THREE-DIMENSIONAL GLOBAL MODELS: ZOOM INTO THE GC

The first model of this kind (see Table 3) is that of Zamudio *et al.* (2002) who study also the propagation of coastal waves into the Gulf, however, this model only 'sees' half the Gulf. López *et al.* (2005) using two models, one the same as Zamudio *et al.* (2002) and the other a model that includes the entire Gulf, studied the effects of

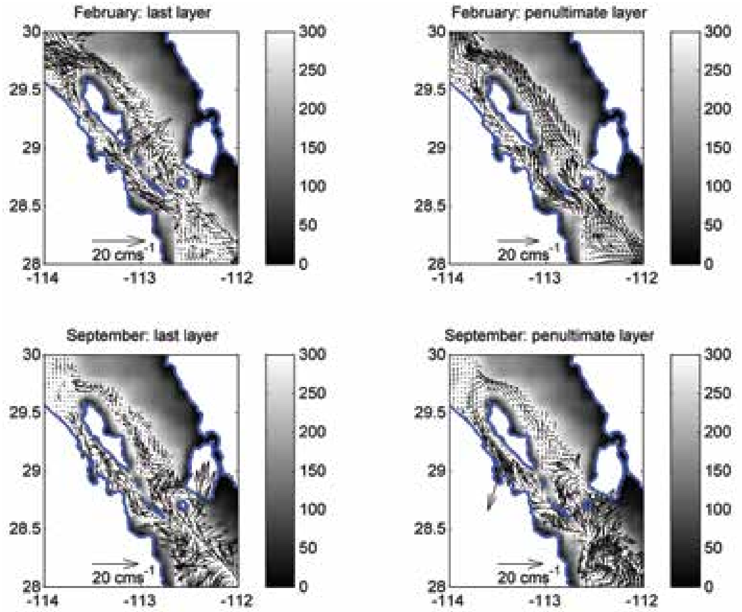

FIGURE 3. February and September bottom circulation. Shown for each month are the last and penultimate model layer velocities for each mesh point. The model was forced with tides and climatological temperature and salinity fields at the mouth, climatological heat and freshwater fluxes and winds at the sea surface. Only one every three vectors are shown.

TABLE 3. Output of large scale numerical models zooming into the Gulf of California. FNL stands for fully nonlinear.

Studies	Forcing	Characteristics	Resolution	Modeled
Bravo (2011)	W, H, PO, MTC	3D, FNL	E-O 3 km N-S 3.3-5.6 km 20 levels	Internal waves
Zamudio *et al.* (2002)	Nearly global, operational, only half Gulf	3D, FNL, baroclinic	2.0×2.3 km, 7 layers	Incursion and evolution of coastal trapped waves generated outside the Gulf
López *et al.* (2005)	Two global models	3D, FNL, baroclinic	2.0×2.3 km, 7 layers and 7.8×9.2 km, 19 vertical-levels	Effect of El Niño on flow exchange

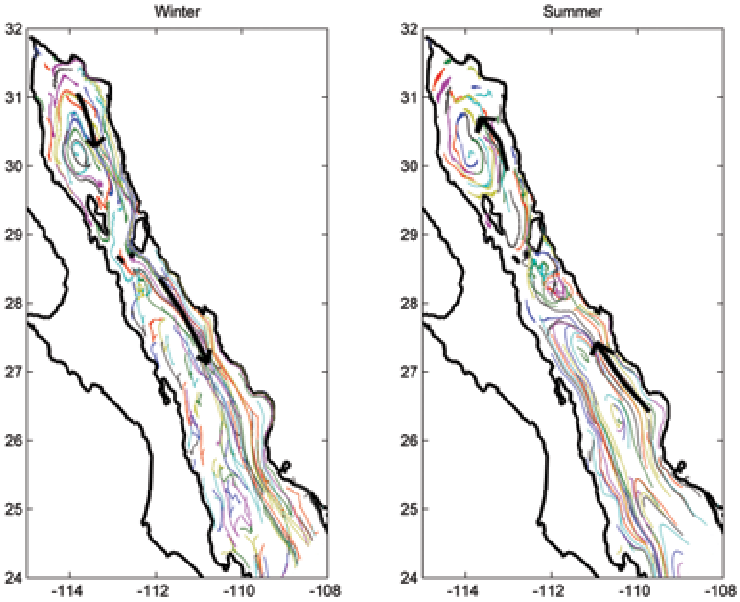

FIGURE 4. Lagrangian circulation for the months of January and July. The trajectories are obtained by integrating the instantaneous velocity fields whose time averaged current are shown in Figure 2. The trajectories follow a three-dimensional path, but the figure shows only the horizontal expression. The arrows are visual aids to indicate the flow direction.

El Niño on the exchange of water within the Gulf. He found an increased inflow in the upper part of the water column compensated with an increased outflow at underlying waters as compared to 'normal' years.

5. APPLICATIONS OF THE NUMERICAL MODELS

The results from Marinone's model (2003) which cover time scales from tidal to seasonal made possible the development of an online tool that predicts sea level and currents overall the Gulf. This tool is available at http://Gulfcal.cicese.mx/ and produces the variables with several options (in a friendly way) to the user. The options range from different regions of the Gulf, different layers, dates, etc. Also, the variables can be reconstructed in such a way that tidal currents and seasonal circulation can be obtained separately.

From the numerical models the Lagrangian circulation of the GC has been characterized in many papers (*e.g.*, Velasco and Marinone 1999, Gutiérrez *et al.* 2004, Marinone 2006, Marinone *et al.* 2008) both with homogeneous and inhomogeneous models and in two- and three- dimensions. Figure 4 shows one-month trajectories

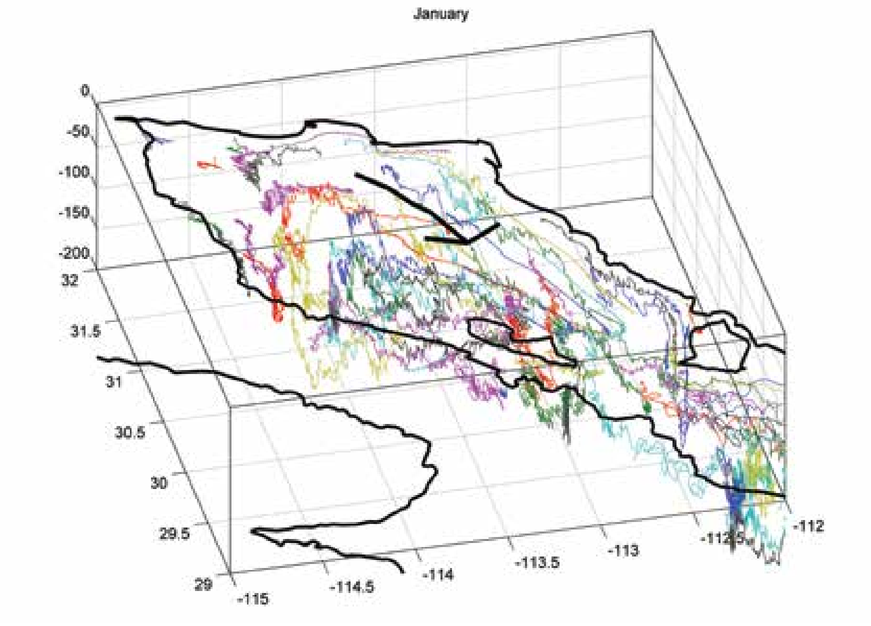

FIGURE 5. Three-dimensional view of some of the trajectories shown in Figure 4 for January. The arrow is a visual aid to indicate the anticyclonic surface flow direction.

for January and July, representatives of the winter and summer circulation. From this type of results, one can visualize the fate of a float (pollutant or any passive tracer), which are not strictly the same as those inferred by eye by observing the Eulerian currents (see Figure 2), especially when strong horizontal and/or vertical shears are present in the velocity field.

The currents shown in Figure 2 are the horizontal component of the surface layer, and the path shown in Figure 4 is only the horizontal expression, however the particles are moving in the three dimensions advected by the full 3D velocity field as, for example, shown in Figure 5 for the northern Gulf. Several applications with this information have been used to study the possible path of larvae and tracers. With these Lagrangian models several indexes such as the time that particles take to leave or escape from a determined area, preferred paths of circulation, final destination after some time, etc., can be constructed, by demand, which can be very useful to characterize the water movements for different applications that require the knowledge of the distribution and evolution of certain properties.

Studies of connectivity, in which the possible destination from one region to another, without the proper knowledge of the species behavior have been done for the northern Gulf (Marinone *et al.* 2008, Peguero-Icaza *et al.* 2008, Sánchez-Velasco *et al.* 2009). The management of the different fisheries needs a proper knowledge of population connectivity/dispersal as well. Useful information can be generated from these models to test and understand the effect of reserves in marine fisheries as did Cudney-Bueno *et al.* (2009). Both, biology and physics are indispensable to properly model the fate of different species in their journey from spawn to settlement. Obviously, with fishes it is more difficult than with species that settle as they dominate the circulation at will when they are adults.

6. FINAL REMARKS

At present, models of the Gulf of California are still in the process of improving and incorporating more realistic forcing. Several projects are also including the behavior of different key species of the Gulf in order to understand and properly manage their fisheries. However, the models results need to be continuously challenged and the best way to do so is to continue measuring the different variables at the sea.

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NEW PHYTOPLANKTON PRODUCTION AND BIOGENIC SILICA AS TOOLS TO ESTIMATE NUTRIENTS AND DISSOLVED INORGANIC CARBON EXCHANGE BETWEEN THE GULF OF CALIFORNIA AND THE PACIFIC OCEAN

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Water exchange between the Gulf of California and the Pacific Ocean (PO) has a significant vertical component (VCWE). Surface (0-200 m) Gulf water flows out to the PO, and deep (200-600 m) water flows into the Gulf. The objective of this chapter is to review biogeochemical methods to estimate the VCWE assuming that the concentration of nutrients in the Gulf are in steady state, and using the necessary net annual input of nutrients from the PO to balance the dissolved Si needed to support the production of opal (mainly diatoms) preserved in the Gulf's sediments, and to balance the nitrate needed to support new phytoplankton production in the whole Gulf (P_{NEW}). Opal accumulation [$(273.3 \pm 6.8)10^9$ moles SiO_2 year^{-1}], and P_{NEW} [$(2586.7 \pm 131.7)10^9$ moles C year^{-1}], were deduced from the literature. Annual averages for H_4SiO_4 and NO_3, for the Gulf's mouth and for the depth intervals 0-200 m and 200-600 m, were used to independently calculate the VCWE needed to balance the opal accumulation and P_{NEW}. The results are 0.23 ± 0.02 Sv in the first case, and (0.67 ± 0.10) Sv in the second (1 Sv = 10^6 m^3 s^{-1}). These relatively low values are only ~3% and ~7% of the whole average water exchange. Thus, most of the exchange between the Gulf and the PO consists of the horizontal component. These VCWE values were used to estimate the net input of dissolved inorganic carbon from the PO into the Gulf ($DIC_{NET\ INPUT}$). After comparing $DIC_{NET\ INPUT}$ with P_{NEW} in both scenarios the results are that the Gulf is a source of CO_2 to the atmosphere, with an average out-gassing of $(7.66 \pm 2.65)\times10^{12}$ and $(18.16 \pm 6.14)\times10^{12}$ grams of carbon in the form of CO_2, in the first and second scenarios, respectively. These values are equivalent to an average of 52.1 ± 18.0 and 123.5 ± 41.8 grams C m^{-2} year^{-1}, respectively. The value for the second scenario is higher than the highest value for the eastern equatorial Pacific as reported in the literature (~108 grams C m^{-2} year^{-1}), which indicates that the value for the first scenario is closer to reality.

Keywords: Gulf of California, Pacific Ocean, water exchange, net input of nutrients, new primary production, CO_2 water-to-air flux.

1. INTRODUCTION

The Gulf of California (GC) is the only evaporative basin of the Pacific Ocean (PO) (Roden 1964). Despite the strong evaporative forcing, the Gulf differs markedly from the Mediterranean and Red seas, which are the primary evaporative basins of the Atlantic and Indian oceans. Fundamental differences between the GC and the Mediterranean and Red sea may be attributed to a net heat gain from the atmosphere in the former, compared to a net heat loss to the atmosphere in the other two (Bray 1988, Lavín and Organista 1988). In the GC there is an annual average net surface heat flux into the sea of ~118 W m^{-2} (Castro *et al.* 1994). This heat has to be exported to the PO somehow; otherwise the Gulf's temperature would be increasing (Lavín *et al.* 1997). The Gibraltar strait, connecting the Mediterranean with the Atlantic, and the strait of Bab-el-Mandeb, connecting the Red sea with the Indian Ocean, has only 14 and 28 km width, respectively. A large entrance to the GC (>200 km wide, and >2500 m deep) allows for a complex circulation to and from the PO (*i.e.*, Roden 1972), including eddies spanning much of the entrance (Emilsson and Alatorre 1997), and that is another significant difference from the Mediterranean and Red sea.

Water exchange between the GC and the PO exhibits spatial and temporal variability, it has a large horizontal component with inflow occurring mostly at the center and eastern side of the Gulf's entrance, and outflow mostly at the western side, but sometimes showing alternating cores of flow into and out of the Gulf (Roden 1972, Castro *et al.* 2006). Integrated transport across the Gulf (T_{INTz} m^2 s^{-1}) is the sum of velocities at each depth. When dealing with the average water exchange for a long period (*i.e.*, a year average), most of the inflow at a certain depth is balanced by the outflow; if there is a difference it has to be balanced by flow in the opposite direction at another depth and this constitutes the vertical component of water exchange (VCWE). Notice that it does not imply a vertical component of advection. When integrating velocity across the Gulf's mouth for each depth the horizontal component of water exchange is eliminated. The VCWE may be defined as the integration of T_{INTz} with depth, for layers between depths with zero T_{INTz}. This VCWE between the GC and the PO consists of less dense, warmer, saltier, and nutrient and dissolved inorganic carbon (DIC) poor surface and near surface water flowing out from the Gulf into the PO, and to balance this flow, relatively deep, denser, colder, fresher, and nutrient and DIC rich water flows into the Gulf. Marinone (2003) used a three-dimensional model to conclude that heat and salt flow out of the Gulf in the top 200 m, and into the Gulf at 200-600 m, and most of the heat budget of the Gulf is defined in the upper 350 m. The average net heat flux is an export of 17×10^{12} W to the PO.

Roden (1958) was the first to estimate the total net water exchange at the mouth of the Gulf by use of salt and water budget considerations. He estimated the inflow as 1.19 Sv (1 Sv = 10^6 m^3 s^{-1}), and the outflow as 1.17 Sv. Roden and Groves (1959) again estimated the water exchange by means of the salt budget computation. The resulting inflow and outflow were each 3.5 Sv. Warsh and Warsh (1971) estimated the water exchange based on geostrophic flow at the mouth of the Gulf for July 1967, to be at least 3.25 Sv and possibly 3.65 Sv in each direction; and their estimate was between 2.57 and 3.5 Sv for February 1957 and May 1959, respectively. Roden (1972) sampled hydrostations with closed spacing (9 km) across the entrance to the Gulf and produced another estimate to be between 10 Sv (inflow) and 12 Sv (outflow), for early December 1969. More recent geostrophic computations and direct measurements of currents confirm that water exchange at the Gulf's entrance is in the order of several Sv (up to >8 Sv) (Lavín *et al.* 2009). But, as indicated by Bray (1988), there is no estimate on how much of this flow includes eddies or frontal meanders which do not contribute to exchange with the PO. Bray (1988) has produced the only estimate of the VCWE but between the northern and central Gulf. She used geostrophic calculations and then integrated transport across the Gulf for each depth, and integrating this with depth water flux was 0.4 ± 0.05 Sv, southward between 0-250 m and northward at 250-500 m. However, her value for T_{INTz} was not zero at 500 m, suggesting a significant vertical component of transport below this depth.

The VCWE between the Gulf and the PO has a very important ecological implication because it is a natural fertilization mechanism for the Gulf. Nutrient concentrations have very weak horizontal gradients across the Gulf (Álvarez-Borrego *et al.* 1978), but it is very well known that they have strong vertical gradients with values increasing with depth (Calvert 1966). We are interested in the VCWE because it causes net input of nutrients from the PO into the GC, and also input of other chemical properties increasing with depth, like trace metals and DIC.

Álvarez-Borrego (2012) and Álvarez-Borrego and Giles-Guzmán (2012) proposed new and independent methods to estimate this VCWE assuming, as a first approximation, that the concentration of nutrients in the Gulf are in steady state, and using the necessary net annual average input of nutrients from the PO to balance the nitrate needed to support new phytoplankton production in the whole GC, and to balance the dissolved Si (because of the pH range of sea water, dissolved Si is in the form of $Si(OH)_4$) needed to support the production of biogenic particles (opal, mostly diatom frustules and radiolarians) that are preserved in the Gulf's sediments. The objective of this chapter is to review Álvarez-Borrego's (2012) and Álvarez-Borrego and Giles-Guzmán's (2012) results, and to analyze Rodríguez-Ibáñez *et al.*'s (2013) application of these results to infer that the Gulf is a source of CO_2 to the atmosphere.

2. NEW PHYTOPLANKTON PRODUCTION AS A TOOL TO ESTIMATE THE VERTICAL COMPONENT OF WATER EXCHANGE BETWEEN THE GULF OF CALIFORNIA AND THE PACIFIC OCEAN

New production is the fraction of total phytoplankton production supported by the input of nitrate from outside the euphotic zone (Dugdale and Goering 1967), mainly from below the thermocline by vertical eddy diffusion and upwelling. Phytoplankton cells use nutrients recycled within the euphotic zone for regenerated production (P_R). Total production is equal to the sum of both new and regenerated production ($P_T = P_{NEW} + P_R$). Álvarez-Borrego (2012) proposed a biogeochemical method to estimate the VCWE between the GC and the PO which is based on using the annual average net input of nitrate needed to support new phytoplankton production in the whole Gulf of California (P_{NEW} moles C year^{-1}). This latter author explored the possibility of other sources of nutrients, besides the input from the PO, and concluded that usable forms of nitrogen input by rivers, agricultural runoff, and N_2 fixation by diazotrophs might add to only ~1.5% of the input of nitrate from the PO.

Hidalgo-González and Álvarez-Borrego (2004) used satellite ocean color data to estimate P_T and P_{NEW} for the Gulf of California. From their data, Álvarez-Borrego (2012) estimated a P_{NEW} annual average of $(31.04 \pm 1.58)10^9$ kg C for the whole Gulf, for non-El Niño years (in this and all following cases the number after ± is one standard error, $s\ n^{-0.5}$). This is equivalent to $(2586.7 \pm 131.7)10^9$ moles C year^{-1}, for the whole Gulf. This P_{NEW} annual average value has to be supported by the annual average net nitrate input from the PO. Redfield *et al.* (1963) proposed a nitrogen to carbon ratio (N:C) for phytoplankton photosynthesis equal to 16:106 when they are expressed in moles. Based on chemical data from isopycnal surfaces, Takahashi *et al.* (1985) proposed a "new Redfield" N:C ratio of 16:122 = 0.131. The formula of the hypothetical mean organic molecule corresponding to this ratio is $(CH_2O)_{80}(CH_2)_{42}(NH_3)_{16}(H_3PO_4)$, which takes into account that marine phytoplankton often contain considerable quantities of lipid materials such as triglycerides and waxes (Pilson 1998). Thus, the nitrate needed to support the annual average P_{NEW} for the whole Gulf is (2586.7 ± 131.7)10^9(0.131) = (339 ± 17)10^9 moles year^{-1}.

An inference may be done on the average vertical component of water fluxes needed for the net annual nitrate input from the PO into the Gulf to sustain P_{NEW} for the whole Gulf. One way to estimate the net input of nitrate, from the PO into the Gulf, is to calculate the transport out of the Gulf in the surface water layer (0-200 m), and into the Gulf in the deep layer (200-600 m), and calculate the difference. These depth limits were chosen based on Marinone's (2003) results, as mentioned above. Proper averages of nitrate concentration (NO_3) for each layer (0-200 and 200-600 m), for the Gulf's mouth, are needed. These NO_3 averages have to be weighted means, where the weighting factor is T_{INTz} at each depth. Álvarez-Borrego (2012) used a similar shape to that of the average of Bray's (1988) integrated transport profiles (m^2 s^{-1}), and Marinone's (2003) results to generate an T_{INTz} profile with relative values ($T_{INT(Z)}$) for 0-600 m, with zero relative integrated transport at 200 and 600 m (see Figure 1). Notice that a depth with zero horizontally integrated velocity (T_{INTz}) is not necessarily without motion; it is a depth with equal input and output of water. Álvarez-Borrego (2012) generated an average NO_3 vertical profile for the mouth of the Gulf and for the 0-600 m depth interval (see Figure 2) and combined it with the $T_{INT(Z)}$ profile to generate weighted averages for nitrate concentrations for the depth intervals 0-200 m, and 200-600 m, respectively: $NO_{3(0\text{-}200)} = \Sigma(NO_{3(Z)*}T_{INT(Z)})/\Sigma(T_{INT(Z)})$, with z changing from 0 to 200 m, and similarly for 200-600 m. The annual NO_3 averages for the mouth of the Gulf are (14.37 ± 1.13)10^{-3}, and (30.45 ± 0.50)10^{-3} moles nitrate m^{-3}, for 0-200 m and 200-600 m, respectively (Álvarez-Borrego 2012).

If the annual average net water flux in and out of the Gulf is represented by X Sv, then the average flux of nitrate out of the Gulf in the surface layer (0-200 m) is (14.37 ± 1.13)10^{-3} moles m^{-3})(10^6X m^3 s^{-1}) = (14.37 ± 1.13)(10^3X) moles s^{-1}, equivalent to (453.2 ± 35.6)(10^9X) moles year^{-1}. Similarly, the average annual flux of nitrate into the Gulf in the deep layer (200-600 m) is (960.3 ± 15.8)(10^9X) moles year^{-1}. The difference is the average annual net input of nitrate from the PO into the Gulf, and it is equal to ((960.3 ± 15.8) – (453.2 ± 35.6))(10^9X) = (507.1 ± 51.4)(10^9X) moles year^{-1}. Making this net input of nitrate equal to the one required to support the P_{NEW} annual average in the whole GC: (507.1 ± 51.4)(10^9)X = (339 ± 17)(10^9); then X = VCWE = (0.67 ± 0.10) Sv (Álvarez-Borrego 2012).

Beman *et al.* (2005) studied the discharge of nutrients from the Yaqui Valley to the Gulf and proposed that agricultural runoff may be fueling large phytoplankton blooms in the Gulf of California. However, Ahrens *et al.*'s (2008) largest estimate of

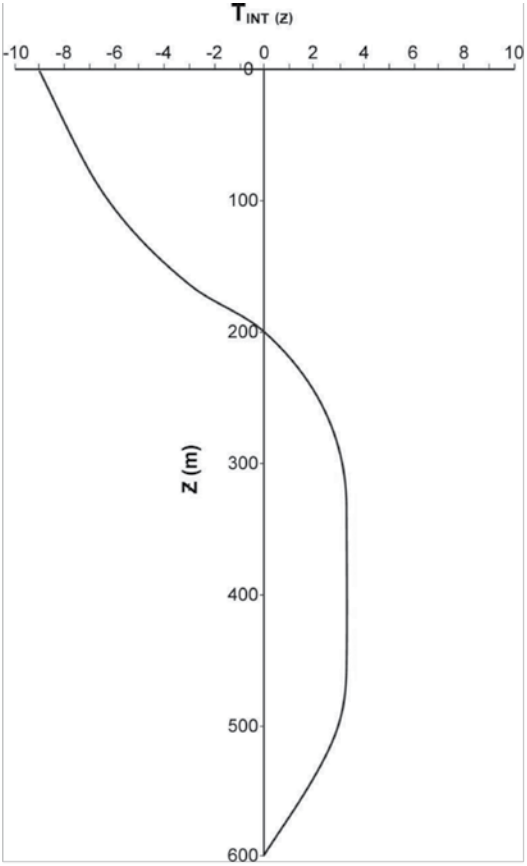

FIGURE 1. Shape of the annual average of the vertical distribution of water transport integrated across the mouth of the Gulf of California, with relative values (taken from Álvarez-Borrego and Giles-Guzmán 2012).

annual dissolved inorganic nitrogen coastal loading from the Yaqui Valley was only $(1.93)10^6$ kg of N (equivalent to $(137.9)10^6$ moles N, mostly in reduced forms), which is only ~0.04% of the net annual input of nitrate from the PO to the GC. Even if Ahrens *et al.*'s (2008) figure is multiplied by five, considering the input of inorganic nitrogen from other agricultural valleys like those of the rivers Mayo, Culiacán, and other smaller ones, the total annual inorganic N input from agricultural runoff to the Gulf is only about ~0.2% of the input from the PO. Agricultural runoff may have an important impact on coastal lagoons and estuaries, but the Gulf's oceanic primary productivity is mainly driven by the input of nutrients from the PO into the GC. On

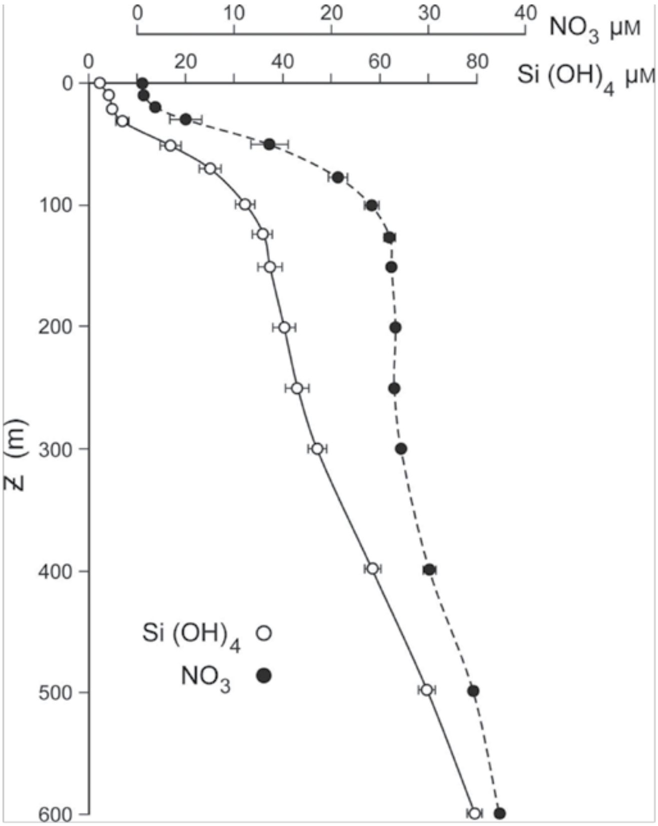

FIGURE 2. Annual averages of the vertical distributions of H_4SiO_4 and NO_3 for the mouth of the Gulf of California. Horizontal bars represent ± one standard error ($s\ n^{-0.5}$) and where it does not show it is smaller than the symbols (taken from Álvarez-Borrego and Giles-Guzmán 2012).

the other hand, White *et al.* (2007) studied N_2 fixation in the central and southern Gulf during summer. They concluded that phytoplankton "blooms" (0.68-0.79 mg chlorophyll a m^{-3}, compared to a regional summer mean of 0.38 mg m^{-3}) due to N_2 fixation are very patchy and episodic, and they only occur throughout the central to eastern Gulf south of the midriff islands, away from upwelling off the western coast and from the mixed waters closed to the midriff islands. Nitrogen fixation supported blooms occur regionally in ~3.7% of the cloud-free satellite data record for summer periods. These presumed N_2 fixation supported blooms may result in an approximately twofold increase in chlorophyll a concentrations and primary productivity, above the regional summer means (White *et al.* 2007). Combining White *et al.*'s (2007) results with those of Hidalgo-González and Álvarez-Borrego (2004) for total primary production in the central and southern Gulf during summer, ~0.09(10^9) kg C for N_2 fixation supported primary production is calculated, and it is only ~0.3% of the above estimate for P_{NEW} ((31.04 ± 1.58)10^9 kg C year^{-1}). N_2 fixation supported primary production is very significant ecologically, but in terms of its contribution to annual P_{NEW} for the whole Gulf it is negligible (Álvarez-Borrego 2012).

3. BIOGENIC SILICA (OPAL) PRESERVED IN THE SEDIMENTS AS A TOOL TO ESTIMATE THE VERTICAL COMPONENT OF WATER EXCHANGE BETWEEN THE GULF AND THE PACIFIC OCEAN

In the Gulf of California, at intermediate depths (500 to 1100 m), the concentration of oxygen in some places is undetectable by the Winkler method. Laminated, diatomaceous sediments are formed where the basin slopes intersect the oxygen minimum in the water column (Calvert 1966). Burrowing organisms do not live in this poorly oxygenated zone, and the absence of biogenic disturbance allows the laminations to become finely developed. The opal content of the sediments of the Gulf and the formation of alternating light and dark millimeter-scale laminae have been studied extensively since the 1939 EW Scripps cruise (*i.e.*, Revelle 1939, 1950, Calvert 1966, DeMaster 1979, Thunell *et al.* 1994). Most of the biogenic silica is preserved in the basins of the central Gulf, but diatoms and radiolarians are also preserved in bio-disturbed sediments throughout the Gulf (Calvert 1966).

DeMaster (1979) sampled six sediment cores and found agreement with Calvert's (1966) data. This latter author studied 150 sediment cores. Thunell *et al.* (1994) sampled two sediment cores and calculated biogenic silica accumulation rates, and they expressed that their estimates were very similar to the average opal accumulation rate of 0.34 g m^{-2} day^{-1} determined by DeMaster (1979) for the entire GC. Multiplying DeMaster's (1979) figure by the area of the whole GC: (0.34(10^{-3}) kg m^{-2} day^{-1})(147x10^9 m^2)(365 days year^{-1}) = 18.24x10^9 kg opal year^{-1}. Since diatom frustules have 10% water (Calvert 1966) the total amount of accumulated silica is 16.42x10^9 kg SiO_2 year^{-1}, and transforming it to grams and dividing by the molecular weight of SiO_2 it is equivalent to 273.3(10^9) moles SiO_2 year^{-1}.

Considering a minimum value for the standard error of this average value equal to ± 2.5% (Calvert 1966), its absolute value is ± 6.8(10^9) moles SiO_2 year^{-1}. This annual average of preserved silica has to be supported by the dissolved Si annual input from the PO to the Gulf (Álvarez-Borrego and Giles-Guzmán 2012).

Álvarez-Borrego and Giles-Guzmán (2012) used the average net annual input of dissolved Si needed to support the production of biogenic silica particles that are preserved in the Gulf's sediments to make an independent estimate of the VCWE, in a similar manner as the one done by Álvarez-Borrego (2012) using the balance between the net input of dissolved nitrate and P_{NEW}. Álvarez-Borrego and Giles-Guzmán (2012) discussed the possibility of other sources of Si, besides the input from the PO to the Gulf, with the conclusion that dissolved Si input from rivers and hydrothermal vents might add to only ~3% of the input from the PO.

Again, one way to estimate the annual average net input of dissolved Si, from the PO into the Gulf, is to calculate the transport out of the Gulf in the surface water layer (0-200 m), and into the Gulf in the deep layer (200-600 m), and calculate the difference. Álvarez-Borrego and Giles-Guzmán (2012) generated an average dissolved Si vertical profile for the mouth of the Gulf and for the 0-600 m depth interval (see Figure 2), and combined it with Álvarez-Borrego's (2012) $T_{INT(Z)}$ profile (see Figure 1) to calculate weighted averages for dissolved Si concentrations for the depth intervals 0-200 m, and 200-600 m, respectively: $H_4SiO_{4(0-200)} = \Sigma(H_4SiO_{4(Z)*}T_{INT(Z)})/\Sigma(T_{INT(Z)})$, with z changing from 0 to 200 m, and similarly for 200-600 m. The annual averages of H_4SiO_4 for the mouth of the Gulf, weighted by $T_{INT(Z)}$, are $(20.23 \pm 1.47)10^{-3}$, and $(57.70 \pm 1.48)10^{-3}$ moles Si m^{-3}, for 0-200 m and 200-600 m, respectively.

If the annual average water flux in and out of the Gulf is represented by X Sv, then the average flux of dissolved Si out of the Gulf in the surface layer (0-200 m) is $((20.23 \pm 1.47)10^{-3}$ moles $m^{-3})(10^6$ X m^3 $s^{-1}) = (20.23 \pm 1.47)(10^3$ X) moles s^{-1}, equivalent to $(640.2 \pm 46.4)(10^9$ X) moles Si year^{-1}. Similarly, the average annual flux of dissolved Si into the Gulf in the deep layer (200-600 m) is $(1819.6 \pm 46.7)(10^9$ X) moles Si year^{-1}. The difference is the average annual net input of dissolved Si from the PO into the GC, and it is equal to $((1819.6 \pm 46.7) - (640.2 \pm 46.4))(10^9$ X) $= (1179.4 \pm 93.1)(10^9$ X) moles Si year^{-1}. Making this net input of dissolved Si equal to the average total annual opal accumulated in the sediments of the whole Gulf: $(1179.4 \pm 93.1)(10^9)X = (273.3 \pm 6.8)(10^9)$; X = VCWE = 0.23 ± 0.02 Sv (Álvarez-Borrego and Giles-Guzmán, 2012).

At the beginning of the 20th century, before the construction of dams, the dissolved Si input from rivers to the Gulf was $9.15\text{x}10^9$ moles Si year^{-1} (Calvert 1966), which was only ~3.3% of the amount needed to support the production of preserved biogenic silica in the sediments of the Gulf. At present the input of dissolved Si by rivers is much smaller because of the large amount of dams. Another possible source of dissolved Si to the Gulf is the fluids from hydrothermal vents like those of Guaymas basin. Álvarez-Borrego and Giles-Guzmán (2012) used data from the literature (Von Damm *et al.* 1985, Campbell and Gieskes 1984) to estimate that hydrothermal vents contribute a maximum of ~2% of the Si needed to support the production of preserved biogenic silica in the Gulf. Furthermore, this input of hydrothermal Si is confined to deep waters closed to the bottom and do not reach the euphotic zone to be utilized by plankton. Thus, the VCWE between the Gulf and the PO remains by far the main source of dissolved Si for the production of biogenic silica particles accumulated in the sediments of the Gulf.

Using their VCWE value, Álvarez-Borrego and Giles-Guzmán (2012) estimated the average net annual input of nitrate from the PO to the GC, and then transformed it to a P_{NEW} value for the whole Gulf. The nitrate export to the Pacific in the 0-200 m layer is $((14.37 \pm 1.13)10^{-3}$ moles $m^{-3})((0.23 \pm 0.02)10^{6}\ m^{3}\ s^{-1})(86400\ s^{1}$ $day^{-1})(365$ days $year^{-1}) = (104.2 \pm 17.2)10^{9}$ moles $year^{-1}$; and the input in the deep layer is $(220.8 \pm 22.8)10^{9}$ moles $year^{-1}$, with a net input into the Gulf of $(116.6 \pm 40.0)10^{9}$ moles $year^{-1}$. Thus, applying Takahashi *et al.*'s (1985) Redfield C:N ratio, P_{NEW} for the whole Gulf is $7.625(116.6 \pm 40.0)10^{9}$ moles C $year^{-1} = (10.67 \pm 3.66)10^{12}$ g C $year^{-1}$ (Álvarez-Borrego and Giles-Guzmán 2012).

4. COMPARISON OF THE NET INPUT OF DISSOLVED INORGANIC CARBON FROM THE PACIFIC OCEAN INTO THE GULF WITH P_{NEW} TO INFER IF THE GULF IS A SINK OR SOURCE OF CO_2 TO THE ATMOSPHERE

The oceans have been considered to be a major sink for CO_2. Hence the improved knowledge of the net transport flux across the air–sea interface is important for understanding the fate of this important greenhouse gas emitted into the earth's atmosphere (Callendar 1938, Siegenthaler and Sarmiento 1993). On the basis of the global distribution of ΔpCO_2 values (ΔpCO_2 = surface water CO_2 partial pressure minus air CO_2 partial pressure = $pCO_{2w} - pCO_{2air}$), a global net ocean uptake flux for anthropogenic CO_2 emissions of 2.0 ± 1.0 PgC yr^{-1} was estimated in a reference year 2000 (one PgC is 10^{15} grams of C in the form of CO_2) (Takahashi *et al.* 2009). Among the four ocean basins, the Atlantic Ocean (north of 50°S) is the strongest sink providing about 60% of the total global ocean uptake, whereas the Pacific (north of 50°S) is nearly neutral. The Indian and Southern Oceans contribute about 20% each to the global uptake flux (Takahashi *et al.* 2002). However, the coastal ocean has been largely ignored in global carbon budgeting efforts, even if the related flows of carbon and nutrients are disproportionately high in comparison with its surface area (Chen-Tung *et al.* 2003).

The wind field over the Gulf of California is essentially monsoonal in nature, from the NW during "winter" and from the SE during "summer". Upwelling occurs off the eastern coast with northwesterly winds ("winter" conditions from December through May), and off the Baja California coast with southeasterly winds ("summer" conditions from July through October), with June and November as transition periods (Roden 1964). Coastal upwelling areas are known to show oversaturation of CO_2 with respect to atmospheric equilibrium because of the input of DIC-rich deep waters (Borges 2005). Besides, the northern Gulf exhibits spectacular tidal phenomena, and in spite of relatively strong stratification during summer, tidal mixing in the midriff islands region produces a vigorous stirring of the water column down to >500 m depth, with the net effect of carrying colder, nutrient-rich water to the surface (Simpson *et al.* 1994) and creating an ecological situation similar to constant upwelling (Álvarez-Borrego 2002). This also has the effect of making the areas around the midriff islands a strong source of CO_2 to the atmosphere (Zirino *et al.* 1997, Hidalgo-González *et al.* 1997).

Rodríguez-Ibáñez *et al.* (2013) used Álvarez-Borrego's (2012) and Álvarez-Borrego and Giles-Guzmán's (2012) VCWE values to calculate the net annual average inputs of dissolved inorganic carbon ($DIC_{NET\ INPUT} = DIC_{INPUT} - DIC_{OUTPUT}$). Rodríguez-Ibáñez *et al.* (2013) compared $DIC_{NET\ INPUT}$ values with the P_{NEW} annual averages to infer if the Gulf acts as a sink or source of CO_2 to the atmosphere.

Rodríguez-Ibáñez *et al.* (2013) considered the entrance to the Gulf a place where DIC is input from the Pacific Ocean into the Gulf, and from there it is transported throughout the Gulf. Steady state of DIC profiles throughout the Gulf was assumed at the scale of annual averages. Their method only requires an annual average DIC profile for the entrance to the Gulf. The Gulf is considered as a box open to the Pacific for water and dissolved components exchange, and also open to the atmosphere for gas exchange (see Figure 3). In order to achieve steady state, once inside the Gulf $DIC_{NET\ INPUT}$ has to be balanced by consumption by new phytoplankton production and water-air CO_2 exchange:

$$DIC_{NET\ INPUT} - P_{NEW} - CO_{2EXCHANGE} = 0,$$
$$CO_{2EXCHANGE} = DIC_{NET\ INPUT} - P_{NEW}$$

If $CO_{2EXCHANGE}$ is positive there is an excess of $DIC_{NET\ INPUT}$ after nitrate has been exhausted by new phytoplankton production, and carbon dioxide flows from the water to the atmosphere; if $CO_{2EXCHANGE}$ is negative there is a deficit of $DIC_{NET\ INPUT}$ and carbon dioxide flows from the atmosphere to the water. This occurs regardless of the particular characteristics of DIC profiles in different regions of the Gulf. Gas exchange occurs with different intensities at different regions of the Gulf according to their particular physical dynamics (mixing and upwelling). Rodríguez-Ibáñez *et al.*'s (2013) objective was to produce an average $CO_{2EXCHANGE}$ estimate for the whole Gulf.

Rodríguez-Ibáñez *et al.* (2013) generated an average DIC profile for the mouth of the Gulf and combined it with Álvarez-Borrego's (2012) average $T_{INT(Z)}$ profile (see

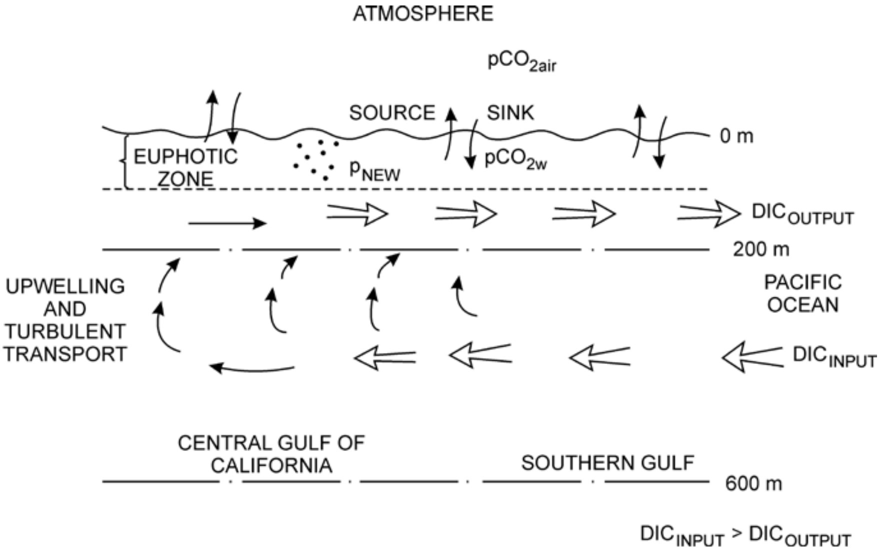

FIGURE 3. A simplified diagram showing the net input of dissolved inorganic carbon ($DIC_{NET\ INPUT}$) and how it could be compared with new phytoplankton production (P_{NEW}) to infer if the Gulf is a sink or source of CO_2 to the atmosphere. $DIC_{NET\ INPUT} = DIC_{INPUT} - DIC_{OUTPUT}$. When $P_{NEW} > DIC_{NET\ INPUT}$ the Gulf is a sink of CO_2; when $P_{NEW} < DIC_{NET\ INPUT}$ the Gulf is a source of CO_2 (taken from Rodríguez-Ibáñez *et al.* 2013).

Figs. 1 and 4) to calculate weighted averages for DIC for each layer, 0-200 m and 200-600 m: $DIC_{(0-200)} = \Sigma(DIC_{(Z)*}T_{INT(Z)})/\Sigma(T_{INT(Z)})$, with z changing from 0 to 200 m; and similarly for 200-600 m. The average DIC for the first 200 m ($DIC_{(0-200)}$), weighted by $T_{INT(Z)}$, is 2.100 ± 0.012 moles m^{-3}; and the respective average for 200-600 m is 2.294 ± 0.006 moles m^{-3}.

The average DIC output from the Gulf to the PO in the 0-200 m layer was calculated multiplying $DIC_{(0-200)}$ (moles m^{-3}) by the water transport (10^6xVCWE $m^3\ s^{-1}$); and similarly for the average DIC input from the PO into the Gulf in the 200-600 m layer. Each of the two results was transformed into an annual DIC flux:

$$DIC_{OUTPUT} = (DIC_{(0-200)} \text{ moles m}^{-3})(10^6\text{xVCWE m}^3\text{ s}^{-1})(86400\text{ s day}^{-1})(365\text{ days year}^{-1})$$

$$DIC_{INPUT} = (DIC_{(200-600)} \text{ moles m}^{-3})(10^6\text{xVCWE m}^3\text{ s}^{-1})(86400\text{ s day}^{-1})(365\text{ days year}^{-1})$$

In order to explore different possibilities for the air-sea exchange of CO_2 in the Gulf, Rodríguez-Ibáñez *et al.* (2013) used two scenarios: in the first one the VCWE is equal to 0.23 ± 0.02 Sv and P_{NEW} is equal to (9.26 ± 3.18)x10^{12} g C $year^{-1}$

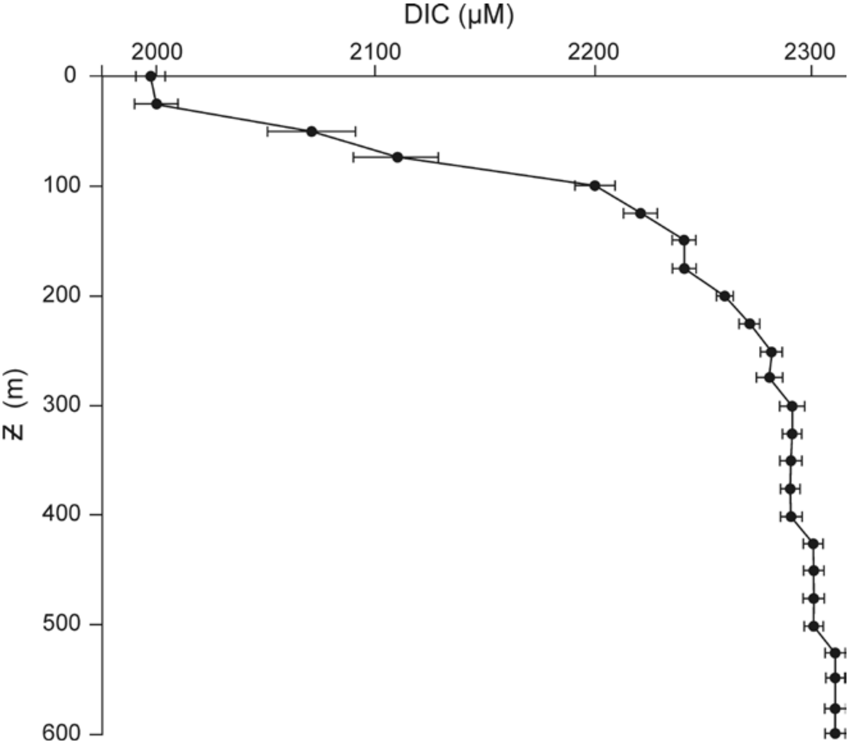

FIGURE 4. Annual average of the vertical distribution of DIC (μM) for the mouth of the Gulf of California. Horizontal bars represent ± one standard error (s $n^{-0.5}$) (taken from Rodríguez-Ibáñez *et al.* 2013).

(Álvarez-Borrego and Giles-Guzmán 2012); in the second scenario the VCWE is equal to 0.67 ± 0.10 Sv and P_{NEW} is equal to (31.04 ± 1.58)x10^{12} g C $year^{-1}$ (Álvarez-Borrego 2012). Standard errors were calculated by Rodríguez-Ibáñez *et al.* (2013) following D'Hainaut (1978). However, the VCWE value for the surface layer (0-200 m) has to always be equal to the one for the deep layer (200-600 m); because of the conservation of mass principle there are no degrees of freedom for these two fluxes to change independently. Since the DIC_{OUTPUT} from the Gulf to the PO is going to be subtracted from the input from the PO to obtain $DIC_{NET\ INPUT}$, it implies that when multiplying the weighted DIC average for each layer by 10^6xVCWE the uncertainty of the VCWE value (± 0.10 Sv in one case, and ± 0.02 Sv in the other) should not be taken into account. For the same reason the uncertainty of the P_{NEW} value calculated by Álvarez-Borrego and Giles-Guzmán (2012) depends only on the uncertainty of the weighted average values of NO_3 for each layer and not on the uncertainty of VCWE. Thus, when subtracting P_{NEW} from $DIC_{NET\ INPUT}$ to infer if there is an excess of CO_2 or vice versa, instead of using Álvarez-Borrego and Giles-Guzmán's (2012) P_{NEW} value [(9.26 ± 3.18)x10^{12} g C year^{-1}], Rodríguez-Ibáñez *et al.* (2013) used the recalculated P_{NEW} value equal to (9.26 ± 1.09)x10^{12} g C year^{-1}.

In the first scenario the average flux of dissolved CO_2 out to the PO in the 0-200 m layer is (2,100 ± 0.012 moles m^{-3})(230,000 m^3 s^{-1})(86,400 s day^{-1})(365 days year^{-1}) = (15.54 ± 0.11)x10^{12} moles year^{-1}. Similarly, the average annual flux of dissolved CO_2 into the Gulf in the 200-600 m layer is (17.15 ± 0.04)x10^{12} moles year^{-1}. The difference is the average annual net input of CO_2 from the PO into the Gulf: $DIC_{NET\ INPUT}$ = [(17.15 ± 0.04) – (15.54 ± 0.11)]x10^{12} = (1.61 ± 0.15)x10^{12} moles year^{-1} = (19.32 ± 1.8)x10^{12} g C year^{-1}. Subtracting P_{NEW} from $DIC_{NET\ INPUT}$: [(19.32 ± 1.8)x10^{12} - (9.26 ± 1.09)x10^{12}] g C year^{-1} = (7.66 ± 2.65)x10^{12} g of carbon per year. This is an excess of net DIC input with respect to that needed to support P_{NEW} and CO_2 has to flow from the water to the atmosphere (Rodríguez-Ibáñez *et al.* 2013).

In the second scenario the average flux of DIC out to the PO in the 0-200 m layer is (2,100 ± 0.012 moles m^{-3})(670,000 m^3 s^{-1})(86400 s day^{-1})(365 days year^{-1}) = (44.37 ± 0.25)x10^{12} moles year^{-1}. Similarly, the average annual flux of DIC into the Gulf in the 200-600 m layer is (48.47 ± 0.13)x10^{12} moles year^{-1}. The difference is the average annual net DIC input from the PO into the Gulf: $DIC_{NET\ INPUT}$ = [(48.47 ± 0.13) – (44.37 ± 0.25)]x10^{12} = (4.10 ± 0.38)x10^{12} moles year^{-1} = (49.20 ± 4.56)x10^{12} grams C year^{-1}. Subtracting P_{NEW} from $DIC_{NET\ INPUT}$: $CO_{2EXCHANGE}$ = [(49.20 ± 4.56)x10^{12} - (31.04 ± 1.58)x10^{12}] grams C year^{-1} = (18.16 ± 6.14)x10^{12} grams of carbon per year. Again, this is an excess of DIC input with respect to that needed to support P_{NEW} and CO_2 has to flow from the Gulf to the atmosphere (Rodríguez-Ibáñez *et al.* 2013). Thus, the Gulf of California behaves as a source of CO_2 to the atmosphere in both scenarios (Rodríguez-Ibáñez *et al.* 2013).

5. DISCUSSION

The values deduced by Álvarez-Borrego and Giles-Guzmán (2012) and Álvarez-Borrego (2012) for the vertical component of water exchange between the Gulf of California and the Pacific Ocean, 0.23 ± 0.02 Sv and 0.67 ± 0.10 Sv, in and out of the Gulf, are annual averages. These relatively low values, possibly only ~3% or ~7% of the whole water exchange, indicate that when considering a particular depth most of the time the inflow from the PO is equal or very similar to the outflow. Thus, most of the exchange between the Gulf and the PO consists of the horizontal component, and this occurs significantly from 0 m to >1000 m (*i.e.*, Roden 1972). Estimates of current speeds by geostrophic calculations are accurate to ±20% at best (Reid 1959). Thus, the small vertical component of water exchange at the Gulf's mouth may possibly be lost within the uncertainty of geostrophic computations. Nevertheless, as mentioned above, Bray (1988) was able to estimate it for water exchange between the northern and central Gulf.

Álvarez-Borrego and Giles-Guzmán (2012) run a sensitivity analysis and found that the value for the VCWE does not vary significantly with changes of the shape of the vertical profile of $T_{INT(Z)}$ and with changes of the average profile of dissolved Si concentration. The relation between the VCWE and the average opal accumulation rate for the entire Gulf is direct and linear. If the average opal accumulation rate is changed by a certain percentage, VCWE does it by the same percentage and in the same direction. Rodríguez-Ibáñez *et al.* (2013) performed a sensitivity analysis to assess the effect of changing the specific alkalinity profile, and the VCWE value, on $DIC_{NET\ INPUT}$. When calculating DIC from pH and alkalinity values, the most critical aspect for attaining accuracy is the calibration of the HCl solution to measure alkalinity. There may be inaccuracies in the estimate of alkalinity, because this calibration is not always performed properly, even though the measurements could be relatively precise. Also, Rodríguez-Ibáñez *et al.* (2013) run an exercise to see the effect of changing the average DIC profile on $DIC_{NET\ INPUT}$ equilibrating the mixed layer waters with the 2013 NOAA atmospheric average pCO_2 value of 396 ppm. Their results show that the $DIC_{NET\ INPUT}$ values do not vary significantly with changes of the specific alkalinity profile; and up to 2013, corrections to the estimates of $DIC_{NET\ INPUT}$ due to the fact that mixed layer waters of the Gulf tend to be equilibrated with an increasing atmospheric pCO_2 may be considered negligible. Since DIC data used by Rodríguez-Ibáñez *et al.* (2013) are from years in the period 1974-1997, they have the effect of a large fraction of the anthropogenic CO_2 that has been absorbed by this region of the ocean. On the other hand, it is reasonable to assume that anthropogenic CO_2 stored in the Gulf of California is practically the same as that of the adjacent Pacific Ocean (~15 moles of CO_2 m^{-2}, Sabine *et al.* 2004), so that it would not make any appreciable difference in the exchange between the two. This storage has accumulated for the last one and a half century and a large fraction of it must be part of the DIC profile that Rodríguez-Ibáñez *et al.* (2013) used.

The Gulf of California behaves as a source of CO_2 to the atmosphere because the slope of the DIC-nitrate relationship is greater than Redfield's ratio in subsurface and deep waters of the Gulf of California (not illustrated) (Rodríguez-Ibáñez *et al.* 2013). When subsurface and relatively deep water are carried to the euphotic zone by upwelling and/or mixing, after all nitrate is consumed by new phytoplankton production there is DIC left as an excess. The Gulf of California is a source of CO_2 to the atmosphere because of the DIC-nitrate relationship, regardless of the VCWE value. The DIC excess over NO_3, at depth, is because of the dissolution of calcium carbonate skeletons (Park 1965); also because of denitrification processes associated to the oxygen minimum zone in the eastern Pacific (Thomas 1966), and to differences of preformed DIC (Park 1965). The processes of calcium carbonate dissolution and denitrification occur along the trajectory of the water masses from their origin at high latitudes, and not only at the Gulf. Calcium carbonate dissolution occurs in waters deeper than ~200 m because of under-saturation with respect to both aragonite and calcite in the Gulf of California (Gaxiola-Castro *et al.* 1978) and in the whole northeastern Pacific Ocean (Park 1968); denitrification occurs at 100-800 m depth in the eastern Pacific Ocean because of nitrate reduction by bacteria when dissolved oxygen concentration is very low (Thomas 1966); and since the deeper the water masses the lower their temperature, deep waters had a larger solubility of gases (including CO_2) at their latitude of origin, when they were in contact with the atmosphere, and hence greater preformed DIC than that of shallow waters (Culberson and Pytkowicz 1970).

The choice of two layers, 0-200 m and 200-600 m, is not the only possible one. Marinone (2003) used a three dimensional model to predict the circulation of the Gulf, and when integrating the average annual circulation predicted by this model across the Gulf's mouth, the VCWE between the Gulf and the PO results in four layers: 0-200 m (0.23 Sv outflow), 200-600 m (0.13 Sv inflow), 600-1,200 m (0.04 Sv outflow), and 1,200-2,600 m (0.17 Sv inflow), with flows as point estimates (S.G. Marinone, CICESE, Ensenada, personal communication) (notice that the sum of outflows and inflows are not equal). However, the annual average net input of dissolved Si with these water inflows and outflows is ~3 times that needed for the production of opal preserved in the sediments of the Gulf. On the other hand, there is no physical known mechanism that would transport nutrients from very deep waters, such as those below 1200 m, to the euphotic zone to be used by phytoplankton.

The net nutrient and DIC input to the Gulf is not transported to the euphotic zone homogeneously throughout it because there are regional differences of the physical dynamics of the Gulf. As Álvarez-Borrego (2012) indicated, upwelling along most of the eastern Gulf with "winter" conditions, cyclonic eddies in different parts of the Gulf, and strong mixing at the midriff islands throughout the whole year (mainly with spring tides and during "winter") are mechanisms that transport deep nutrient and CO_2-rich waters to the euphotic zone. The midriff islands region is the area within the Gulf with the highest CO_2 water-to-air fluxes throughout the whole year; it is the area with the largest values of pCO_{2w}, as mentioned above (*e.g.*, Zirino *et al.* 2007). On the other hand, Calvert's (1966) figure 7 shows the opal distribution in surface sediments of the Gulf and suggests that Guaymas basin might be the place with highest phytoplankton production. Álvarez-Borrego and

Lara-Lara (1991) used ^{14}C data to conclude that highest productivities are found during winter-spring and in the Guaymas Basin (up to >4 g C m^{-2} day^{-1}). This may be because of strong upwelling events and the horizontal transport of nutrient rich mixed waters carried from the relatively near midriff islands into this basin (Álvarez-Borrego 2012). The "winter" upwelling off the eastern coast might be the area with the second highest CO_2 water-to-air fluxes in the Gulf.

There are clear evidences that there is a large seasonal variation of phytoplankton biomass in the Gulf, with diatoms as an important component, and also a temporal variation of circulation in the Gulf, with a strong seasonal component. There is high phytoplankton biomass and production during winter and spring associated to a general anticyclonic circulation, and low biomass and production during summer and autumn associated to a general cyclonic circulation (Santamaría-Del Ángel *et al.* 1994a, Hidalgo-González and Álvarez-Borrego 2001, 2004, Kahru *et al.* 2004, Bray 1988, Marinone 2003). In accordance with this, opal fluxes from the euphotic zone to the sediments are high during winter and spring and low during summer and autumn (Thunell *et al.* 1994). Also, there is interannual variability dominated by El Niño events (Baumgartner and Chriestensen 1985, Santamaría-Del Ángel *et al.* 1994b, Hidalgo-González and Álvarez-Borrego 2004, Kahru *et al.* 2004). This indicates that an estimate of the VCWE between the PO and the Gulf as an annual average is a first approximation to reality and there are opportunities for future work on its time variability.

The nitrate required by P_{NEW} for the whole Gulf of California has to be compensated by an export, from the Gulf to the PO, of reduced forms of inorganic nitrogen (after respiration), dissolved organic nitrogen (DON), and particulate organic nitrogen (PON); and also an export of PON from the pelagic ecosystem to the sediments of the Gulf. Álvarez-Borrego (2012) estimated that ammonium export to the Pacific is only ~3% of the nitrogen in the form of nitrate that is required by P_{NEW}. Based on estimates by Thunell *et al.* (1994), export of PON to the sediments is only ~3% of the nitrogen required by P_{NEW}. In the water column, PON is only ~3% of DON. Thus, the majority of reduced nitrogen that is exported from the Gulf to the PO is in the form of DON. Thus, the Gulf of California is an autotrophic system that imports inorganic dissolved nutrients from the Pacific Ocean and exports mainly dissolved organic matter.

Based on 1.6 Sv of water exchange at the Gulf's mouth (Roden and Groves 1959), Calvert (1966) calculated that the Pacific Ocean net supply is approximately 10^{11} kg of dissolved silica per year. Calvert's (1966) objective was to demonstrate that there was more than enough dissolved Si input from the Pacific Ocean to support the accumulation of biogenic silica in the Gulf, and that there was no need for dissolved

Si input from rivers. But his estimate for the net input of dissolved Si from the PO was about seven times the amount needed for the production of silica preserved in the sediments of the Gulf, and that was because he considered Roden and Groves's (1959) water exchange value (1.6 Sv) as if all of it was the VCWE, without any horizontal component.

With a vertical component of water exchange of (0.67 ± 0.10) Sv, instead of 1.6 Sv, the estimate for the net input of dissolved silica from the PO is decreased by a factor of 0.67/1.6 = 0.4, resulting in $(4)10^{10}$ kg SiO_2 $year^{-1}$, which is still more than double than the estimate for the biogenic silica preserved in the sediments of the Gulf ($(1.5)10^{10}$ kg SiO_2 $year^{-1}$). This difference suggests that the value 0.67 Sv might be an overestimation for the VCWE between the Gulf and the PO, and this could happen if Hidalgo-González and Álvarez-Borrego (2004) overestimated their P_{NEW} values. Biogenic silica preserved in the sediments of the Gulf has been measured extensively and directly with samples taken from cores since the 1939 EW Scripps cruise (Revelle 1939, 1950, Calvert 1966, DeMaster 1979, Thunell *et al.* 1994). On the other hand, $^{15}NO_3$ incubations have not been carried out in the Gulf, and it is not possible to have an idea of the accuracy of the estimates of P_{NEW} deduced from modeling satellite data because there are no P_{NEW} in situ ship data to compare both types of results.

Furthermore, Rodríguez-Ibáñez *et al.* (2013) transformed their values of the Gulf's CO_2 output to the atmosphere for both scenarios into average values in grams m^{-2} $year^{-1}$: in the first scenario their average value is 52.1 ± 18.0 grams m^{-2} $year^{-1}$; and in the second scenario it is 123.5 ± 41.8 grams m^{-2} $year^{-1}$. The maxima water-to-air annual average CO_2 fluxes of the world's ocean, as reported by Takahashi *et al.* (2009), are between 24 and 108 grams m^{-2} $year^{-1}$, in places like the eastern equatorial Pacific Ocean, which has continuous upwelling. The Gulf of California is almost at equilibrium with the atmosphere during "summer" conditions, with exception of the midriff islands region, and during "winter" upwelling occurs mostly at the eastern side. Thus, an annual average CO_2 flux per unit area for the whole Gulf cannot be larger than the maximum for places like the eastern equatorial Pacific. This indicates that the first scenario is more acceptable with an average CO_2 output to the atmosphere of $(7.66 \pm 2.65)x10^{12}$ grams C $year^{-1}$ for the whole Gulf, and that the VCWE value of (0.23 ± 0.02) Sv is closer to reality than (0.67 ± 0.10) Sv. This CO_2 input from the Gulf to the atmosphere is only ~1.7% of the annual CO_2 output to the atmosphere of the whole eastern equatorial Pacific (0.48 Pg C $year^{-1}$, Takahashi *et al.*, 2009), which has a very large area compared to that of the Gulf. But, when adding up all coastal areas of the whole world's ocean, the figure may be a very significant one (*i.e.*, Chen-Tung and Borges 2009).

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PHYTOPLANKTON BIOMASS AND PRODUCTION AT THE ENTRANCE OF THE GULF OF CALIFORNIA

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The region adjacent to the mouth of the Gulf of California is in the transitional area between temperate and warm waters of the eastern tropical Pacific off Mexico. A historical perspective of its phytoplankton biomass and productivity (PP) is given based on data from *in situ* ^{14}C experiments and estimates from semi-analytical models using chlorophyll *a* concentrations (Chl_{sat}) and photosynthetically active radiation (PAR_{sat}) from monthly composites of the satellite sensor SeaWIFS. Coastal stations have biomass and productivity values up to two times higher than those of the offshore waters. During El Niño events both Chl and PP values are reduced at the mouth region. Upwelling events, the intrusion of tropical surface waters and the El Niño events are the main sources of phytoplankton biomass and productivity variability at the region.

Keywords: entrance to the Gulf of California, chlorophyll *a*, primary production, ^{14}C method, satellite imagery.

1. INTRODUCTION

Traditionally, the Eastern Tropical Pacific Ocean off Mexico (ETPM) has been described as an area of low phytoplankton productivity (PP) as characterized by its clear waters, attributed to low chlorophyll a concentrations (Chl) (*e.g.*, Stevenson 1970). However, satellite ocean colour imagery shows that at certain times of the year (mainly spring) the entrance to the Gulf of California develops relatively high pigment concentrations, in the region off Cabo Corrientes (see Figure 1) (García-Reyes 2005, Pennington *et al.* 2006). This feature is apparent in many images (*e.g.*,

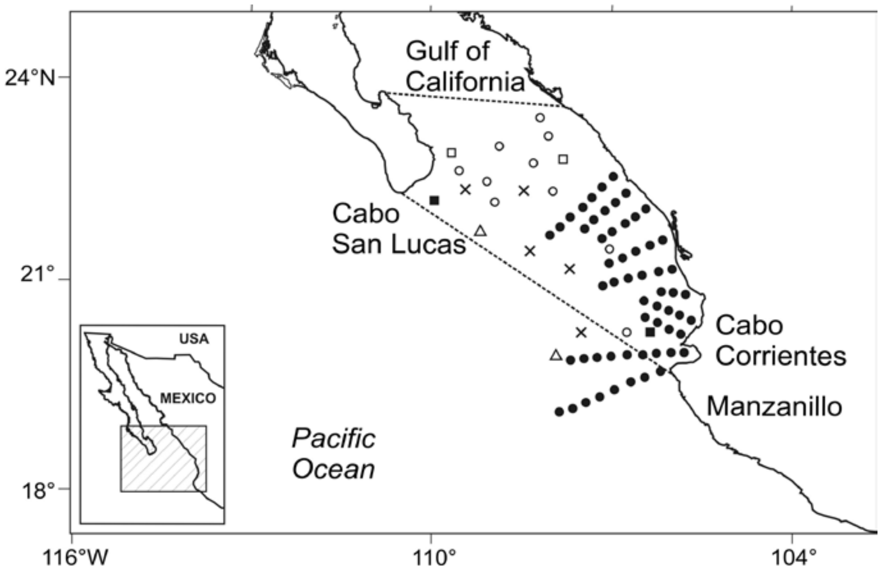

FIGURE 1. Mexican eastern tropical Pacific, showing the entrance to the Gulf of California and stations for primary productivity experiments: O Zeitzschel (1969), x Leet and Stevenson (1969), Δ Gaxiola-Castro and Álvarez-Borrego (1986), □ Valdez-Holguín and Lara-Lara (1987), ■ Lara-Lara and Bazán-Guzmán (2205), ● López-Sandoval *et al.* (2009a). The zone within the dotted lines shows the area used for remote sensing data by Santamaría-Del Ángel *et al.* (1994) and Hidalgo-González and Álvarez-Borrego (2004).

fig. 12 of Pennington *et al.* 2006, and images and field data from López-Sandoval *et al.* 2009a, b).

For the purpose of the following discussion, the entrance to the Gulf of California will be considered roughly as that between a line connecting Cape San Lucas and Cape Corrientes and a line connecting La Paz with Topolobampo (see Figure 1). This is a transitional zone that has a very complicated and dynamic oceanographic structure (Álvarez-Borrego 1983). The region adjacent to the mouth of the Gulf of California is in the transitional area between temperate and warm waters of the ETPM, and therefore it presents thermal and haline fronts. The presence of mesoscale structures such as eddies and meanders has also been reported (Torres-Orozco *et al.* 2005, Lavín *et al.* 2006, Zamudio *et al.* 2007). The region is considered one of the most productive areas for pelagic fisheries, in particular for yellowfin tuna (Stevenson 1970, Torres-Orozco *et al.* 2005).

Ship primary productivity and biomass data for the area adjacent to the mouth of the Gulf of California are very scarce and provide only single point estimates for some locations, mainly offshore (Zeitzschel 1969, Leet and Stevenson 1969, Gaxiola-Castro and Álvarez-Borrego 1986, Valdez-Holguín and Lara-Lara 1987, Lara-Lara and Bazán-Guzmán 2005). More recently, López-Sandoval *et al.* (2009a, b) generated primary productivity data for the region off Cabo Corrientes performing 14C incubation experiments and from models based on remote sensing data. Santamaría-Del Ángel *et al.* (1994) generated satellite derived chlorophyll a (Chlsat) time series (1978-1986), and Hidalgo-González and Álvarez-Borrego (2004) generated a PP time series (1997-2002) also based on satellite data, with both data sets including information for the entrance to the Gulf.

The objective of this contribution is to review the information on the phytoplankton biomass and productivity variation at the entrance to the Gulf of California in the context of the physical environment, with emphasis on the annual and interannual variability.

2. THE PHYSICAL ENVIRONMENT

The entrance to the Gulf of California is located between 18° and 23°N, and from 105° to 110°W (see Figure 1). There are three surface waters at the entrance: Cold California Current water of low salinity (≤ 34.60), which flows southward along the west coast of Baja California; warm eastern tropical Pacific water of intermediate salinity (34.65≤ S ≥34.85), which flows into the area from the southeast; and warm highly saline (S ≥ 34.90) Gulf of California water (Roden and Groves 1959, Stevenson 1970). Winds are from the northwest during winter and spring ("winter" conditions), and from the southeast during summer and autumn ("summer" conditions), with maximum speeds during "winter". This causes a strong annual variation of phytoplankton biomass and productivity because of upwelling with "winter" conditions and very warm and oligotrophic waters with the "summer" intrusion of tropical surface waters. Upwelling conditions in this region may result at the eastern coast with alongshore winds during "winter" (Roden 1972); and also as a result of the interaction between coastal currents and the physiography, mainly at Cabo Corrientes, similar to the generation of cold-water plumes off Point Conception, California, as described by Fiedler (1984). Coastal upwelling has an important effect on the nutrient supply to the euphotic zone and hence on Chl and PP. The geostrophic currents are equatorward during "winter", including the area south from Cabo Corrientes (thus propitious to upwelling), while during "summer" they are poleward (see Figure 7 in Keesler 2006). The latter cause downwelling near the coast, and the sinking of the thermocline, with oligotrophic waters at the surface during summer and autumn.

Warsh *et al.* (1973) presented the vertical distribution of phosphate concentrations across the entrance to the Gulf. Their graphs show surface phosphate values of ~0.2 μM increasing rapidly with depth to ~2.3 μM at 100 m. Álvarez-Borrego and Giles-Guzmán (2012) reported, for the entrance region, annual mean surface values of nitrate and silicate concentrations of 0.35 ± 0.15 μM, and 2.7 ± 0.65 μM, respectively; increasing with depth to values at 100 m of 24.1 ± 0.9 μM, and 32.6 ± 1.9 μM, respectively (the numbers after ± is a standard error). Thus, high nutrient concentrations are found in very shallow waters and it takes relatively little energy to bring them up to the euphotic zone (Álvarez-Borrego *et al.* 1978).

López-Sandoval *et al.* (2009a) reported the temperature variability for the region off Cabo Corrientes, during three oceanographic cruises in May and November 2002, and June 2003. During May, mean sea surface temperature (SST) was 27.1ºC, for November it was 28.4ºC, and for June it was 27.4ºC. The SST distribution for May showed a coastal band of cool SST, suggesting upwelling. This was confirmed by the vertical distribution of potential temperature (see Figure 2a) showing the isotherms rising toward the coast and a surface mixed layer thinning in the same direction for the line of hydro-stations that cross the cool SST area. On the other hand, SST distribution for November showed evidence of coastal downwelling (see Figure 2b). During June SST was quite patchy but with the lowest SST values at the most inshore locations, which showed the presence of a very weak upwelling. The 24 and 26ºC isotherms showed an uplifting close to the coast (see Figure 2c). Thermocline near the coast (see Figure 2) was deeper during November (~80 m) than during June 2003 (50 m).

3. PHYTOPLANKTON BIOMASS

Phytoplankton biomass *in situ* ship data expressed as chlorophyll *a* concentration are very scarce for this region; however, they provide a general idea of the spatial and temporal variability. For example, Lara-Lara and Bazán-Guzmán (2005) reported the Chl size fractionated contribution at two locations during winter of 1999, the euphotic zone mean Chl values were from 0.32 to 0.95 mg m^{-3}, and the integrated concentrations varied from 16.8 to 24.9 mg Chl *a* m^{-2} (see Table 1). Nanophytoplankton (cells < 20 um) was the dominant fraction at both stations.

Based on data from the satellite sensor Coastal Zone Color Scanner (CZCS), Santamaría-Del Ángel *et al.* (1994) generated Chl_{sat} time series (1978-1986) for three locations at the entrance to the Gulf. Their Figure 2b shows a dramatic difference between the Chl_{sat} values of the location close to the tip of the Peninsula and those of the location close to mainland, with a very clear and strong effect of "winter"

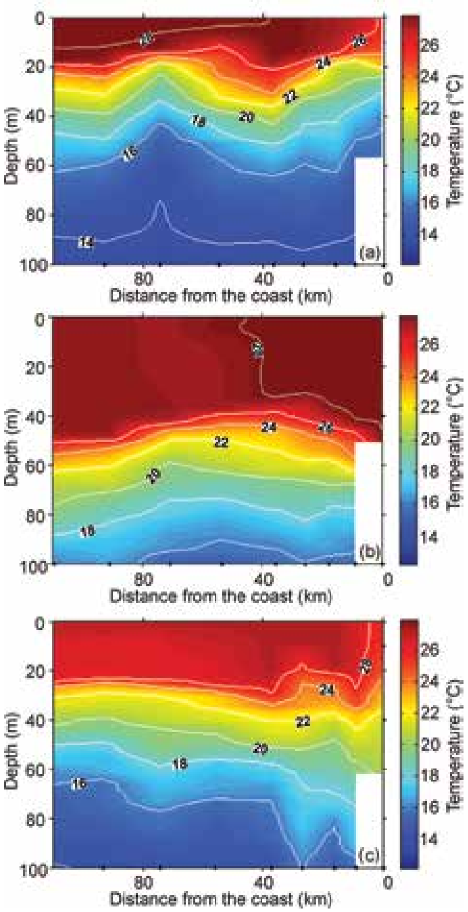

FIGURE 2. Vertical cross-section of potential temperature off Cabo Corrientes (from López-Sandoval *et al.* 2009a).

upwelling at the eastern side of the entrance (Chl_{sat} values often up to >5 mg m^{-3}), and with very low Chl_{sat} values most of the time at the western side of the entrance (very few occasions with values up to 2 mg m^{-3}). Zuria-Jordán *et al.* (1995) also used CZCS data to describe the temporal and spatial distribution of phytoplankton biomass across the entrance to the Gulf. Off Cabo Corrientes, high values occurred from January through May (5 to 8 mg m^{3}), indicating that this area experience strong seasonal upwelling. El Niño 1982-1984 had a clear effect on pigment concentration, with Chl_{sat} values <1 mg m^{3} at the whole entrance to the Gulf most of the time during September 1982–December 1984 (see Figure 2b of Santamaría-Del Ángel *et al.* 1994). A recurrent front was observed by Zuria-Jordán *et al.* (1995) off Cabo San

TABLE 1. Comparison of average range values for $PP^{14}C$ (g C m^{-2} d^{-1}), PPmod (g C m^{-2} d^{-1}), Chl (mg m^{-3}) and Chlint (mg m^{-2}) for the entrance of the Gulf of California.
Sources: 1. Zeitzschel (1969); 2.*Leet and Stevenson (1969) are mg C m^{-3} d^{-1}; 3. Gaxiola-Castro and Alvarez-Borrego (1986); 4. Lara-Lara and Bazán-Guzmán (2005); 5. Hidalgo-González and Alvarez Borrego (2004); 6. López-Sandoval *et al.* (2009a); 7. López-Sandoval *et al.* (2009b)

Sampling Date	Chla	Chlint	$PP^{14}C$	PPmod	Source
November-December			0.45-0.95		1
April-August			1.30-38.8*		2
January			0.19-1.40		3
January 1999	0.32-0.95	16.8-24.9	0.16-0.17		4
All year (1997-2002)					
- cool season	0.36-0.92			1.16-1.85	5
- warm season	0.24-0.55			0.39-0.49	5
May 2002	2.0	180	0.10-0.63		6
November 2002	0.8	155	0.11-0.30		6
June 2003	0.8	50	0.25-0.80		6
May 2002	0.47-0.60			0.55-1.50	7
November 2002	0.17-0.42			0.31-0.38	7
June 2003	0.27			0.41-0.70	7

Lucas with the strongest pigment concentration gradients at the end of spring and beginning of summer, during non-El Niño years. Based on monthly composites of the satellite sensor SeaWIFS, Hidalgo-González and Álvarez-Borrego (2004) reported Chl_{sat} for the Gulf of California, including an area from the mouth down to the northern part of Cabo Corrientes. Average Chl_{sat} values for this area during the cool season (end of November–end of June) varied from 0.36 to 0.92 mg m^{-3}, while during the warm season (July–early November) they varied from 0.24 to 0.55 mg m^{-3} (see Table 1).

López-Sandoval *et al.* (2009a) reported maximum Chl values for the region off Cabo Corrientes varying from 11.3 mg m^{-3} in May 2002 to 0.8 mg m^{-3} in November 2002 and June 2003 (see Figure 3). The spatial distribution of *in situ* surface Chl for May (see Figure 3a) showed the highest concentrations in the coastal region, in correspondence with the lowest SST, with maximum subsurface values up to 11 mg m^{-3} just off Cabo Corrientes. The surface Chl distributions for November and June (see Figures 3b and 3c) were very homogeneous. During May, the mean euphotic zone Chl was 180 mg Chl m^{-2} (see Table 1). However, there was a clear gradient

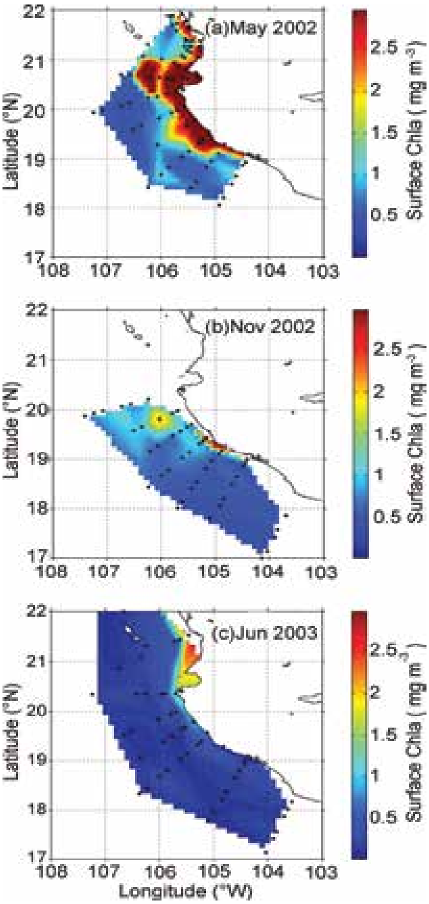

FIGURE 3. In situ surface chlorophyll *a* during (a) May 2002, (b) November 2002, and (c) June 2003 (from López-Sandoval *et al.* 2009a).

with stations close to shore (<60 km from the coast) containing higher integrated Chl (255 mg Chl m^{-2}) than those offshore (105 mg Chl m^{-2}). During November, the mean integrated Chl was 155 mg Chl m^{-2} with no clear onshore-offshore gradient (see Table 1). The lowest Chl values were found in June, with mean integrated Chl of 50 mg Chl m^{-2} (see Table 1), again with higher values onshore (72 mg Chl m^{-2}) than offshore (30 mg Chl m^{-2}).

López-Sandoval *et al.* (2009b) reported Chl$_{sat}$ from monthly composites of the satellite sensor SeaWIFS, for May and November 2002, and June 2003, for the oceanic region off Cabo Corrientes. The May Chl$_{sat}$ distribution showed relatively high values south of Cabo Corrientes, with highest values in the inshore zone (see

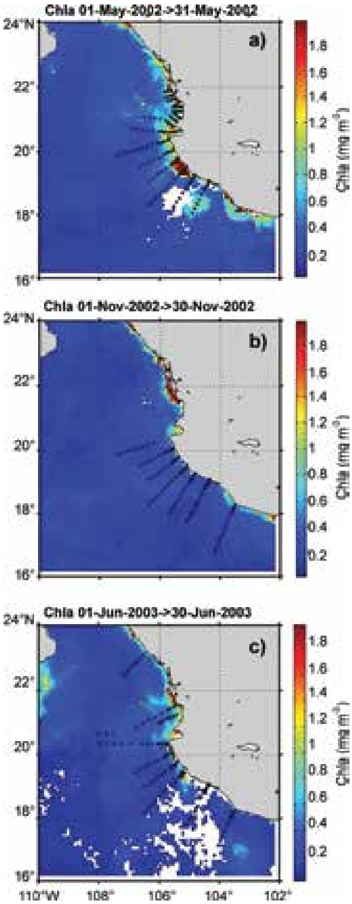

FIGURE 4. SeaWIFS monthly chlorophyll *a* (mg m^{-3}) composites for: (a) May 2002, (b) November 2002, and (c) June 2003 (from López-Sandoval *et al.* 2009b). The dots represent the hydro-stations of the three cruises of López-Sandoval *et al.* (2009a). The white areas in a and c panels indicate the presence of clouds during the whole month.

Figure 4). The June Chl_{sat} distribution also showed relatively high values in the inshore zone, but with a much smaller spatial coverage than that of the May composite (see Figure 4). The November Chl_{sat} distribution showed in general very low values, with few exceptions in the inshore zone north of Cabo Corrientes (see Figure 4). The monthly means Chl_{sat} for May were 0.60 and 0.47 mg m^{-3} for the inshore and the offshore zones, respectively; for November they were 0.42 and 0.17 mg m^{-3} for the inshore and the offshore zones, respectively; and for June they were 0.27 mg m^{-3} for both zones (see Table 1).

4. PRIMARY PRODUCTIVITY

The first reports on PP rates for the mouth of the Gulf of California were done by Zeitzschel (1969) based on half-day incubations (6h). Their integrated values ranged from 0.45 to 0.95 g C m^{-2} d^{-1} for November and December (see Table 1). Leet and Stevenson (1969) measured surface primary production for the region between Mazatlán, Cabo San Lucas and the Tres Marias islands, and their values ranged from 1.3 to 38.8 mg C m^{-3} d^{-1} for April to August (see Table 1). Gaxiola-Castro and Álvarez-Borrego (1986) reported primary productivity rates for two stations close to the entrance of the Gulf in January, ranging from 0.19 to 1.40 g C m^{-2} d^{-1} (see Table 1). Owen and Zeitzschel (1970) reported for the eastern tropical Pacific and average annual cycle from 0.13 to 0.32 g C m^{-2} d^{-1}, with maximum productivity in early spring and a secondary peak in August-September. Lara-Lara and Bazán-Guzmán (2005) reported the PP size fractionated contribution for two locations and for winter 1999; the euphotic zone mean PP values were from 0.86 to 1.65 mg C m^{-3} h^{-1}, and the euphotic zone integrated PP rates varied from 0.16 to 0.17 g C m^{-2} d^{-1} (see Table 1). Nanophytoplankton (cells < 20 um) was the dominant fraction at both stations.

López-Sandoval *et al.* (2009a) reported the spatial and temporal variability of PP for the region off Cabo Corrientes, for May and November 2002 and June 2003. The integrated local PP values for May varied from 0.10 to 0.63 g C m^{-2} d^{-1} with a mean value of 0.36 g C m^{-2} d^{-1} (see Table 1). The onshore stations averaged 0.46 g C m^{-2} d^{-1}, while for the offshore locations the average integrated PP was 0.29 g C m^{-2} d^{-1}. For November the integrated PP values were lower, with a mean value of 0.20 g C m^{-2} d^{-1}, also with an onshore–offshore gradient, varying from 0.30 g C m^{-2} d^{-1} onshore to 0.11 g C m^{-2} d^{-1} offshore (see Table 1). In June the integrated PP mean value was 0.44 g C m^{-2} d^{-1}. During this cruise the mean PP varied from 0.51 g C m^{-2} d^{-1} close to shore to 0.25 g C m^{-2} d^{-1} offshore (see Table 1).

Hidalgo-González and Álvarez-Borrego (2004) and López-Sandoval *et al.* (2009b) calculated the integrated total (PP_{mod}) and new phytoplankton production (PP_{new}) (g C m^{-2} d^{-1}) for the mouth of the Gulf of California, and the oceanic region off Cabo Corrientes, respectively. This was done with semi-analytic models from the literature and using Chl_{sat} and photosynthetically active radiation (PAR_{sat}) from monthly composites of the satellite sensor SeaWIFS. The average PP_{mod} for the whole entrance region, as reported in Hidalgo-González and Álvarez-Borrego's (2004) time series (1997-2002), varied from year to year in the range 1.16 - 1.85 g C m^{-2} d^{-1} during the cool seasons, and in the range 0.39 - 0.49 g C m^{-2} d^{-1} during the warm seasons (see Table 1).

Meanwhile, López-Sandoval *et al.* (2009b) reported for May 2002 an average PP_{mod} for the inshore zone much larger (1.50 g C m^{-2} d^{-1}) than that for the offshore zone (0.55 g C m^{-2} d^{-1}) (see Table 1). Average PP_{mod} for both inshore and offshore zones of November 2002 were close to each other (0.38 and 0.31 g C m^{-2} d^{-1}, respectively) (see Table 1). Average PP_{mod} values for June showed a clear gradient with a higher inshore value than the one for the offshore zone, 0.70 and 0.41 g C m^{-2} d^{-1}, respectively (see Table 1).

Rigorous comparison of satellite-derived PP_{mod} values with average of results from ^{14}C incubations is difficult due to the very different time and space characteristics of these measurements (Hidalgo-González and Álvarez-Borrego 2004). Nevertheless, it is interesting to compare both kinds of data. The PP_{mod} average values from López-Sandoval *et al.* (2009b) largely overestimated (they are between double and triple) the PP_{14C} average values from López-Sandoval *et al.* (2009a) for both inshore and offshore zones. However, in agreement with the PP_{14C} results reported by López-Sandoval *et al.* (2009), PP_{mod} values were highest for May (within the relatively intense upwelling season), they were followed by those for June (during the upwelling relaxation period), and they were lowest for November when stratification was strongest. It is clear from all the PP_{14C} data reported for the region that the photosynthetic rates show that phytoplankton production is very patchy in this region of the ocean and that the PP_{mod} average values may be much more representative than instantaneous point estimates.

5. RESPONSE OF PHYTOPLANKTON BIOMASS AND PRODUCTIVITY TO COASTAL UPWELLING

Thermocline depths are very important for phytoplankton, which depends on irradiance and on the supply of nutrients to perform their two most important physiological functions: photosynthesis and growth. In regions like the eastern tropical Pacific where the thermocline is very shallow, the euphotic zone can be nutrient-enriched with a relatively low wind, increasing phytoplankton productivity (Estrada and Blasco 1985). Pennington *et al.* (2006) indicatet that in the eastern tropical Pacific the depth of the thermocline (nutricline) is controlled by three interrelated processes: a basin-scale east/west thermocline tilt, a basin-scale thermocline shoaling at the gyre margins, and local wind-driven upwelling. In our case the two first processes are not of much relevance because our whole study region is relatively close to the coast.

Upwelling in this region has previously been reported to occur from March through June, in response to the predominant north-westerly winds (Roden 1972, Garcia-Reyes 2005, Torres-Orozco *et al.* 2005). However, López-Sandoval *et al.*

(2009a) used the upwelling index and indicated that during 2002-2003 it started in January in the region off Cabo Corrientes, upwelling was relatively intense in March-May, relaxing in June, and there was no upwelling from July through December. Their May 2002 Chl_{sat} composite showed strong upwelling south from Cabo Corrientes, with high Chl_{sat} values near the coast. They showed also that local upwelling causes periods of enhanced chlorophyll and primary productivity in the inshore area, relative to the offshore area. Their data showed that both PP and Chl were two-fold higher in the coastal stations than in the oceanic region. The highest mean PP rates were registered for the coastal region during the spring cruises (May 2002 and June 2003; 465 and 512 mg C m^{-2} d^{-1}, respectively), and they argue that this was due to coastal upwelling. They showed that for the May 2002 cruise there were low-SST and high-Chl waters in the coastal stations, and the vertical distribution of isotherms for this cruise (see Figure 2a) also showed uplifting of the thermocline toward the coast. It is very likely that the spatial patterns of PP for the region off Cabo Corrientes are, in general, a response to the supply of nutrients from below the thermocline. Unfortunately no nutrient data are available for this region. On the other hand, during late autumn (November 2002 cruise) the lowest Chl (<0.2 mg Chl m^{-3}), PP (<200 mg C m^{-2} d^{-1}), and assimilation ratios were registered. This was probably due to the absence of upwelling, coupled with a deeper mixed layer and a strong thermocline (López-Sandoval *et al.* 2009b). Santa María-Del-Ángel *et al.* (1999) and Hidalgo-González and Álvarez-Borrego (2004) reported that the strong warm season depletion of primary production at the entrance to the Gulf was because of the invasion of equatorial surface waters (ESW). This warm surface water, up to >30 °C, causes very strong water-column stratification, greatly decreasing the effect of upwelling on the phytoplankton biomass and primary production. The vertical salinity distribution reported by López-Sandoval (2007) clearly show the low surface values inshore indicating the presence of the Surface Equatorial Water Mass, with warm and low nutrient waters. Water column stratification acts as a barrier to nutrient inputs from below the mixed layer (Mann and Lazier 1991). Therefore, López-Sandoval *et al.* (2009a, b) confirm the report by Pennington *et al.* (2006) that during spring the enrichment of the Cabo Corrientes region is mainly due to upwelling events.

6. RESPONSE OF PHYTOPLANKTON BIOMASS AND PRODUCTIVITY TO EL NIÑO EVENTS

Santamaría-Del Ángel *et al.* (1994) reported a dramatic suppression of Chl_{sat} at the entrance to the Gulf during El Niño 1982-1983, with values down to ~20% of those for non-El Niño years, but with a relatively small impact in the central and northern Gulf. This was very consistent with Mee *et al.* 's (1985) Chl (1979-1983) time series obtained for a location at the mouth of the Gulf, 30 km from the eastern coast, which showed that Chl values for winter dropped from ~10 mg m^{-3} in 1981-82 to <2 mg m^{-3} in 1983.

Hidalgo-González and Álvarez-Borrego (2004) also reported the effect of El Niño event in the entrance to the Gulf region. Their Chl_{sat} time series (1997-2002) show a clear interannual variation, with lower values in 1997-1998 than during the other "winters". During the other cool seasons there was no clear south to north gradient of integrated PP. During the warm season Chl_{sat} average values for the whole Gulf were similar to those for the entrance region during the cool season and with El Niño event (with the exception of the big islands region). The summer intrusion of the ESW into the Gulf of California produces every year an effect on primary production stronger than that of an El Niño event with winter conditions (González-Hidalgo and Álvarez-Borrego 2004).

7. CARBON FLUXES

New primary production (PP_{new}) is the fraction of PP supported by the input of nitrate from outside the euphotic zone (Dugdale and Goering 1967), mainly from below the thermocline by vertical eddy diffusion (Eppley 1992). It is an estimate of oceanic particle flux in the global carbon cycle. The description of the temporal and spatial variability of PP_{new} may give us an idea of the variability of the flux of organic matter out of the surface layer. For example, Hidalgo-González and Álvarez-Borrego (2004) reported from their time series (1997-2002) a range of PP_{new} values from 0.38 to 0.48 g C m^{-2} d^{-1} during the cool season and from 0.25 to 0.31 g C m^{-2} d^{-1} during the warm season; and for the Cabo Corrientes region López-Sandoval *et al.* (2009b) reported that PP_{new} varied from 0.03 to 0.60 g C m^{-2} d^{-1}. Although organic particle flux has not been measured in our region of interest, and data needs to be generated on this issue for a clear understanding of its benthic ecological dynamics, in any case the PP_{new} seasonality in the region shows that this flux of organic matter is much lower during summer and autumn than during the upwelling season.

8. CONCLUDING REMARKS

With *in situ* and satellite data, López-Sandoval *et al.* (2009b) identified three periods for the phytoplankton dynamics in the region off Cabo Corrientes: first the intense upwelling period (spring), which presented relatively high phytoplankton biomass and production rates; second the upwelling relaxation period (late spring-early summer), when the maxima PP were measured; and third the summer-autumn period, with a deep mixed layer capping a strong thermocline and with minimum Chl and PP. These environmental periods were more evident in the coastal locations (<60 km from the coast). In general, phytoplankton biomass and production rates in the coastal locations were up to two times those of the offshore stations.

It is clear that the region at the entrance to the Gulf, mainly that off Cabo Corrientes, exhibits significant seasonality (hydrography, phytoplankton biomass and productivity rates). This agrees with the comment of Pennington *et al.* (2006) that seasonal cycles are weak over much of the open-ocean eastern tropical Pacific, but that several eutrophic coastal areas do exhibit substantial seasonality. Undoubtedly, this is a response to the physical and chemical environmental variability of the region caused by upwelling that enhances the rates of nutrient supply to maintain high levels of primary production, above those of oligotrophic waters in tropical regions (López-Sandoval *et al.* 2009b).

The "winter" PP_{14C} and PP_{mod} values for the entrance to the Gulf of California were of similar magnitudes as the values reported for other productive regions of the Mexican Pacific coast. For example, Álvarez-Borrego and Lara-Lara (1991) reported 26 PP_{14C} data for "winter" conditions of the central Gulf of California with an average of 1.43 g C m^{-2} d^{-1}, they reported 12 values for the big islands region of the Gulf with an average of 2.1 g C m^{-2} d^{-1} , and they reported four values for the northern Gulf with an average of 1.1 g C m^{-2} d^{-1},compared to the May value of 1.50 g C m^{-2} d^{-1} for the inshore zone off Cabo Corrientes. Also, the spring inshore PP_{mod} rates are comparable to the satellite-derived values reported by Hidalgo-González and Álvarez-Borrego (2004) for the upwelling season of the Gulf of California (1.16 - 1.91 g C m^{-2} d^{-1}). The PP rates were also comparable to those reported for other regions in the Pacific such as the Gulf of Tehuantepec (Robles-Jarero and Lara-Lara 1993, Fiedler 1994, Lara-Lara and Bazán-Guzmán 2005, Fiedler and Talley 2006, López-Calderón *et al.* 2006, Pennington *et al.* 2006), and the California Current System (Aguirre-Hernández *et al.* 2004, Martínez-Gaxiola *et al.* 2007).

The high PP values observed for the coastal locations off Cabo Corrientes shows that this is an area of high fertility during spring. We conclude that upwelling events, the intrusion of southern eastern tropical Pacific surface waters and El Niño events are the main sources of phytoplankton biomass and production variability at the entrance to the Gulf of California.

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MANGROVE STRUCTURE AND DISTRIBUTION DYNAMICS IN THE GULF OF CALIFORNIA

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The structure and distribution of the mangroves in this region are related primarily to the tectonic origin and by both the local weather and hydrological conditions. On the West Coast of the Gulf of California mangroves are limited to small patches of predominantly dwarf sized trees. In contrast, the East Coast of the Gulf, having a larger coastal alluvial plain and numerous rivers, supports a higher mangrove structure and a larger distribution. New technological advances in Earth observation satellites are now improving our ability to map the mangroves within the Gulf. However, without proper field verification, the accuracy of such mapping endeavors cannot be properly assessed. The mangroves in this region have been particularly impacted by hydrologic modifications and thus new efforts that include the use hydrologic modeling have been considered in order to restore them. New techniques that involve genetic microsatellites are also being employed to identify the presence of different mangrove populations within this region.

1. INTRODUCTION

The mangrove forest structure and distribution in the Gulf of California are mainly related to the tectonic origin, the regional weather conditions and the local geomorphology and hydrological conditions. This region is characterized mainly by a mixture of arid ecosystems with deciduous tropical forest. The States surrounding the Gulf of California are Baja California and Baja California Sur (west coast Gulf of California), Sonora, Sinaloa and Nayarit (east coast Gulf of California).

The mean annual rainfall is less than 600 mm, but the range of annual variations is considerable (200 to 800 mm/year) and is in accordance to the number and intensities of hurricanes/tropical storms which reach the coast. The hurricane belt is considered to be in the area of the mouth of the Gulf of California because more than 80% of annual tropical depressions-hurricanes of the Oriental Pacific occur in this region.

The tectonic state of the region is considered as neo-trailing-edge coast (Inman and Nordstrom 1971, Carranza-Edwards *et al.* 1975). The west coast of the Gulf of California produces an absence or a very narrow continental shelf (1 to 5 km) with predominantly rocky shores and small coastal lagoons. Combined with the arid climatic conditions, mangrove structure and distribution is limited to small patches of mangroves predominantly dwarf mangrove (< 2m height) with a narrow fringe mangrove less than 4 meters high adjacent to tidal channels and coastal lagoons. In contrast, the east coast of the Gulf of California (Sonora, Sinaloa and north of Nayarit) contain larger coastal alluvial plains and numerous rivers which provide for a higher mangrove structure (5 to 12 m height) and distribution with climatic conditions that vary from arid to sub-humid. Consequently, some of the most extensive mangrove stands and seasonal floodplains of the Pacific coast of the Americas are located in this region (Marismas Nacionales in Sinaloa and Nayarit).

The climate of this region varies from temperate arid (Sonora and both Baja California), warm (mean annual temperature > 26 C) and semi-arid to warm sub-humid for the rest of the region (Sinaloa, Nayarit, 800–1200 mm, Garcia 1973). Typically heavy seasonal rainfalls occur mainly in the summer months (July to September) and these are strongly influenced by hurricanes. Evaporation rates ranges from 1800–2000 mm. Most of the rivers of this region have a small hydrological basin with the exception of the Yaqui and Mayo rivers basins in Sonora and the Santiago river in Nayarit, flowing seasonally to intermittent from south to north (Arriaga-Cabrera *et al.* 1998b, Atlas 1990).

The intertidal vegetation consists predominantly of 4 species of mangroves: red mangrove (*Rhizophora mangle*), white mangrove (*Laguncularia racemosa*), black mangrove (*Avicennia germinans*) and button mangrove (*Conocarpus erectus*). In Baja California Sur, local peoples consider another tree (*Maytenus phyllanthoides*) as "sweet mangrove". Mangroves are discontinuously distributed along the region with few extensive mangrove forests in Topolobampo-Ohuira, San Ignacio-Navachiste-Macapule, Bahía de Santa María and Ensenada del Pabellón in Sinaloa and in Marismas Nacionales along the border of Sinaloa and Nayarit (see Figure 1: 2-5 and 7, Flores-Verdugo 1992). In the Baja California east coast, the mangroves are mainly fringe mangrove of a few meters width. An important factor that defines the species and structural development of mangroves in this region is the soil salinity. Black mangrove (*A. germinans*) is the most tolerant to high soil salinities (> 50 < 70 psu)

FIGURE 1. The Gulf of California and the location of the sites of reference: 1. Jitzamuri-Bacorehuis (Sinaloa), 2. Topolobampo-Ohuira bay (Sin.), 3. San Ignacio-Navachiste-Macapule bays (Sin.), 4. Santa María Bay (Sin.), 5. Ensenada del Pabellón coastal lagoon (Sin.), 6. Huizache-Caimanero coastal lagoon (Sin.), 7. Marismas Nacionales estuarine complex (Sin.-Nayarit), 8. Bahía de Concepción (BCS), 9. Ensenada de La Paz (BCS), 10. Bahía de los Ángeles (BC), 11. Coronado (Smith) island (BC) and 12. Colorado delta (BC, Sonora).

and thus the most dominant dwarf mangrove species (< 2 m height) landwards of a mixed very narrow fringe forest of red, white and black mangrove (> 4 m). This later fringe mangrove is found along the edge of the lagoons and tidal channels where soil salinities are < 50 psu. In general, fringe and dwarf mangroves are associated with extensive hyperhaline seasonal flood plains ("marismas") with or without saltwort *Salicornia* spp. and *Batis maritima* or even with salt pans (> 90 psu, Jiménez, 1998).

The forest structure increases towards the south as the rainfall increases and in areas with important freshwater input from rivers (Flores-Verdugo *et al.* 1992).

Mixed freshwater wetlands of cattail (*Typha* spp.) with mangroves can be found in Chiricahueto–Ensenada del Pabellón and Patolandia in Bahía de Santa Maria, Sinaloa.

The region has several coastal lagoons and, according to Lankford´s (1977) classification, are predominantly of the type Barred Inner Shelf subtype Gilbert-Beaumont Barrier lagoons and in Nayarit the subtype Strand Plain Depression with multiple sand barriers in Marismas Nacionales (Teacapán-Agua Brava-Las Haciendas). In the latter, Curray *et al.* (1969) estimated the presence of more than 128 sub parallel ridges formed by successive accretion by sand deposition when the transgression of the eustatic sea level slowly rose several times between 3,600 and 4,750 B.P.

The presences of numerous shell middens ("conchales") of *Tivela* sp. and oyster (*Crassostrea* spp.) of more than 1,500 year BP in the region of Marismas Nacionales indicates human presences since those times.

The sand beaches are a continuous component in Sonora, Sinaloa, and Nayarit interrupted only by the rivers / lagoons inlets. Baja California coast is predominantly a rocky coast with small and narrow beaches backed with small coastal lagoons surrounded by mangroves from Bahía de los Ángeles and Coronado (Smith) island including Concepción Bay, to Ensenada de La Paz and Los Cabos) (see Figure 1: 8-11).

There are several coastal classifications for this part of Mexico related to geological, tectonic, morphogenesis and biological characteristics (Carranza-Edwards *et al.* 1975, Lankford (1977), Flores-Verdugo *et al.* (1992) and Contreras-Espinosa (1993). Ortiz-Perez and Espinosa-Rodriguez (1990) also consider a geodynamical classification. According to those authors the region can be classified as being predominantly Prograding Coast (advancing of the coastline toward the ocean by sedimentation). However, the opposite occurs in one point, specifically in front of the Colorado river-estuary where it is related to deltaic inactivity or submersion (see Figure1: 12). One important characteristic of several shallow coastal lagoons of this region is the exposure of extensive areas to the air as a consequence of the high evaporation rate during the dry season. For example, more than 70% of the surface of Huizache-Caimanero is dried during the dry season and, moreover, the cracking of the exposed soil is believed (Arenas & de la Lanza, 1981) to have an important role in the release of nutrients when it is subsequently flooded (see Figure 1: 6).

The Teacapán-Agua Brava-Marismas Nacionales is the most extensive mangrove area of this region (150,000 ha). It is also quite unique with several large homogeneous areas of white mangrove (*L. racemosa*). The region has been studied in aspects of mangrove structure, litterfall, leaf degradation, aquatic primary productivity and fish community dynamics presenting densities as high as 3, 203 trees ha^{-1}, basal areas from 14 to 29.6 m^2 ha^{-1} and litterfall near to 1 kg m^2 yr^{-1}. One interesting aspect of this system is the high concentrations of humic substances that develop during the wet season (> 150 mg l^{-1}) from the mangroves detritus resulting in a red color of the water (Flores-Verdugo *et al.* 1992). The environmental implications of the high concentrations of humic substances in this region are still unknown. The litterfall of several fringe mangroves of the region is also considerable high compared to other regions (*i.e.* Caribbean). There is no clear explanation why mangroves with such relatively low forest structure are as productive in litterfall as well developed riverine mangroves (Flores-Verdugo *et al.* 1987, 1993, Felix-Pico *et al.* 2006).

Earth observational satellites for mangrove monitoring and mapping: Potential use and challenges for Northwest Mexico. In order to properly manage and monitor mangrove forests it is essential that updated maps, indicating the extent and condition of these forested wetlands, be available to resource managers. Such maps might be extremely important for identifying ideal locations for mangrove restoration or for simply examining impacts on mangroves resulting from hydrological modifications, whether natural or anthropogenic. In the past such monitoring activities were extremely costly and time consuming often involving traditional techniques of aerial photographic interpretation and/or extensive in the field biophysical data collection (*e.g.* tree height, tree diameter). This later approach is particularly logistically difficult given the remoteness of mangrove forests and the harsh environment conditions associated with these forests (*e.g.* tidal fluctuations, loose substrate). Consequently, it is no surprise that there have been numerous attempts, even in Northwest Mexico (Kovacs *et al.* 2001, Berlanga-Robles and Ruiz-Luna 2002, Kovacs *et al.* 2004, Fuente and Carrera 2005, Kovacs *et al.* 2005, Kovacs *et al.* 2006, Kovacs *et al.* 2008a, Kovacs *et al.* 2008b, Kovacs *et al.* 2009), to use Earth observational satellites to replace this aspect of mangrove forest management.

Earth observational satellites can provide repetitive coverage of the most remote mangrove forests and they can be readily processed as digital data (*i.e.* manipulated) to provide digital classified maps of mangrove types (*e.g.* dwarf mangrove, tall mangrove). In particular the focus so far has been the use of traditional optical remote sensing platforms such as LandSat MSS, LandSat TM, SPOT and more recently the higher spatial resolution satellites (*e.g.* 1 m on the ground pixel size) such as IKONOS, QuickBird and GeoEye (Walters *et al.* 2008). These optical sensors use the reflection of the Sun's energy off the Earth surface to collect and analyze information on land cover/use features including mangroves. These sensors collect information from the visible area of the electromagnetic spectrum (~400–700 *nm*) as well as the non-visible near infrared (~760–900 *nm*). This later region is extremely useful for monitoring the health of vegetation including mangroves. In particular, very high reflectance in the infrared is indicative of relatively healthy plants and, conversely, low reflectance in the infrared occurs for unhealthy or senescent plants. In contrast, water almost completely absorbs this type of electromagnetic energy. For comparative sake, Figure 2 shows an image of Isla La Palma (Sinaloa) taken using the QuickBird Earth observation satellite in both natural color composite and false color infrared composite. The very bright red in the later image is indicative of very healthy mangrove along the edge of the island which contrasts with the very poor condition of mangroves located more inland that has a very low red coloration.

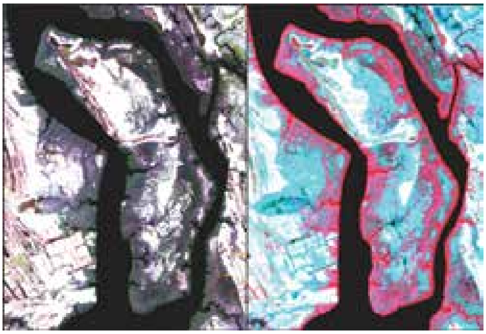


FIGURE 2. Linear enhanced QuickBird Earth observing satellite images of Isla la Palma (22°37'N, 105°40' W) using a natural color composite (left) and a false color infrared composite (right).

Consequently, these data can be used to map the state of mangrove forests (*e.g.* healthy, poor condition, dead) or to extract information associated with mangrove biomass such as Leaf Area Index (LAI) which is a good proxy for health. Alternatively, these data can also be used to determine hydrological data associated with mangroves, including areas of open water which appear black in the images due to its high absorption of infrared energy.

The selection of Earth observing satellite for mangrove monitoring does alter the quality of data that can be derived. With regards to the optical sensors, the very high spatial resolution images (*e.g.* IKONOS, QuickBird), which are often shown in Google Earth, are required in order to map mangroves at the species level (*e.g.* separate *L.racemosa* from *R. mangle*) or for extracting LAI. For example, IKONOS and QuickBird data have been used successfully to map estimated mangrove LAI for the Agua Brava (Kovacs *et al.* 2005) and the Teacapan Estuarine (Kovacs *et al.* 2009) areas, respectively, within the Marismas Nacionales. However, these satellite data are expensive, have limited swath coverage, and historical records are limited. In contrast, the traditional sensors such as LandSat and SPOT have larger swath coverage, are considerably cheaper if not free, and have been recording images of the Earth for decades. The key limitation for these coarser spatial resolution satellites (*e.g.* 30 meter pixel size) is the inability to separate mangroves at the species level. However, these traditional data can be used to separate and map mangroves from other land features as well as providing qualitative maps of mangrove forest condition (*e.g.* healthy, poor condition, dead). In addition to optical sensors, Synthetic Aperture Radar (SAR) Earth observing satellites are now being assessed as an alternative to optical satellites for mangrove monitoring and mapping. Unlike the optical, these sensors do not rely on the Sun's energy but rather emit and receive

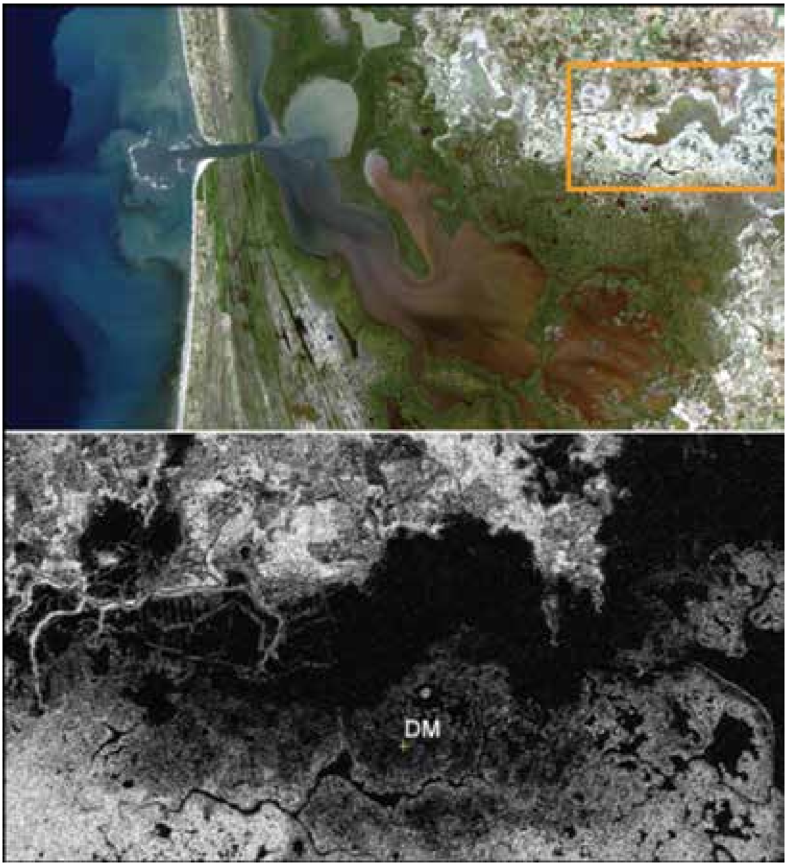
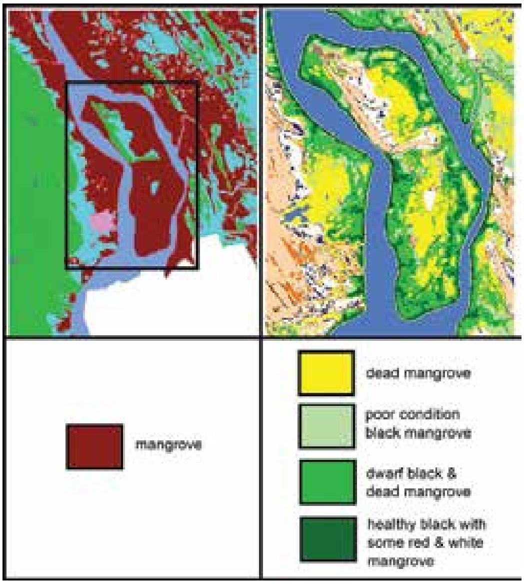


FIGURE 3. An enhanced natural color composite image of the Agua Brava lagoon (22°09' N, 105° 30' W) from the optical sensor (AVNIR) of the ALOS Earth Observing satellite (top). Below is an enhanced SAR (*i.e.* radar) image, the subset shown above, using the radar sensor (PALSAR) of the same Earth observing satellite. Note that the dead mangrove (DM) region is readily identified by both sensors.

their own microwave energy (*e.g.* RadarSat-2 C-band 5.4 *GHz*). As a result they can register mangroves at night and, unlike optical sensors, can register through clouds. In addition, SAR can provide information on the geometry and dielectric properties of the target it is measuring. Although promising, only a few studies, many of them conducted in Northwest Mexico (Kovacs *et al.* 2006, Kovacs *et al.* 2008a, Kovacs *et al.* 2008b), have so far examined SAR in relation to mangrove forest monitoring. The results suggest that SAR is particularly useful, either alone or in conjunction with optical satellite data, for monitoring the health of mangrove forests undergoing degradation. For example, in Figure 3 the large dead white mangrove (*L. racemosa*) area is just as easily identified in the SAR image as in the optical image. Specifically, the healthy trees are white (*i.e.* radar intensity) in the SAR image because the leaves deflect the emitted radar signal back to the satellite. In contrast, in the absence of leaves there is no signal from the dead stands as the emitted radar signal (L-band, HV polarimetry) simply deflects away off the ground with no return to the satellite.

Although many studies have shown the great potential for mapping and monitoring mangroves with Earth observing satellites, one should always be vigilant of the mapping results. This is especially true if no field verification (*i.e.* accuracy assessment) was conducted in conjunction with the satellite image mapping procedure. An example of conflicting results from satellite mapping of mangroves can be found for the Sinaloan section of the Marismas Nacionales, which is considered the largest mangrove system of Northwest Mexico, if not of the Pacific Coast of the Americas. Four recent mangrove mapping exercises all using traditional LandSat Earth observing satellite data have resulted in conflicting results. Two studies (Berlanga-Robles and Ruiz-Luna 2002, Fuente and Carrera 2005), which employed a simple mangrove/non-mangrove classification approach have indicated a considerable extent of mangrove forest and, moreover, that over time these forests have been expanding in this system. In stark contrast, studies by Kovacs *et al.* (2001, 2008b), using a more elaborate mangrove classification system (*e.g.* dead mangrove, poor condition mangrove), indicated an extremely degraded mangrove system that appears to be worsening. Using a subset of this study area, Isla La Palma, we see in Figure 4 the contrasting results from these conflicting approaches. Although considered mangroves by Fuente and Carrera (2005), many of these mangrove stands are in fact dead or in a considerable state of degradation. Using higher spatial resolution satellite data this poor state of mangrove health for the Isla La Palma has recently been confirmed (Kovacs *et al.* 2009). Moreover, recent SAR images are also suggesting a poor state for this important mangrove system. In Figure 5, it is apparent that large areas in the northern region of Marismas Nacionales (lagoon Agua Grande) considered as mainly mangrove forest by some researchers (Berlanga-Robles and Ruiz-Luna 2002, Fuente and Carrera 2005) are in fact degraded mangrove or saltpan since they show little or no radar backscatter signal (*i.e.* black tone) in the SAR image.

In summary, the use of Earth observing satellites to map and monitor mangroves is now becoming the norm in Mexico as in other countries. The current transition in the use of traditional coarser spatial resolution optical satellites to higher spatial resolution ones will improve our ability to map and monitor these forests. Moreover, with the advent of newer SAR systems being used in conjunction with optical sensors it is anticipated that the accuracies of mapping mangrove forests will improve



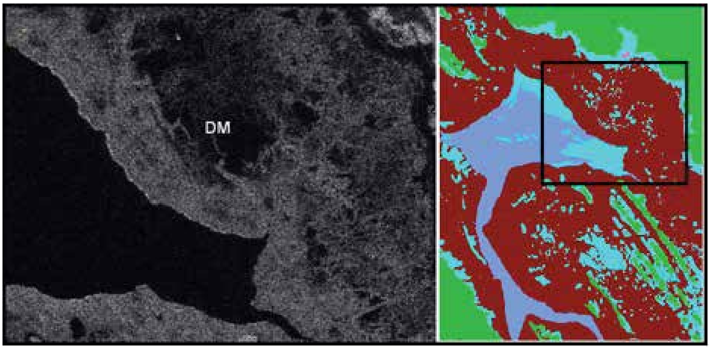


FIGURE 4 (ABOVE). A comparison of mangrove classifications for the Isla la Palma based on LandSat Earth observing satellite data as employed by Fuente and Carrera (2005) on the left (modified from DUMAC 2005) and, on the right, by Kovacs *et al.* (2008b). FIGURE 5 (BELOW). A comparison of a recently classified map based on LandSat data (Fuente and Carrera 2005) indicating mangroves in the dark red color (image on right) with an enhanced ALOS PALSAR image (image on left). Note the large area of dead mangrove (DM) and saltpan in the PALSAR image which is identified mainly as mangrove in the classified map.

considerably. Finally, it is important to reiterate that although Earth observing satellites can be extremely beneficial for mapping the extent and condition of mangroves of Northwest Mexico, without proper field verification (*i.e.* map accuracy assessment) the results from such procedures should be taken with some level skepticism.

2. MANGROVE DISTRIBUTION, HYDROPERIOD, HUMAN IMPACTS AND MITIGATION

With few exceptions the restoration of mangroves in the northwest of Mexico considered only reforestation without any knowlwdge of the local hydrological dynamics and thus have been very prone to failure (Toledo *et al.* 2001, Benitez-Pardo 2004, and Strangman *et al.* 2008). It is postulated that mangrove distribution is affected by microtopography, frequency of tidal flooding and salinity (Cintrón *et al.* 1985, Jimenez and Lugo 2000). In particular, the type of coastal wetland found is often determined by the hydroperiod and the level of salinity present. The effects of tides are considered important factors in mangrove development and growth, with the tides helping to recycle nutrients and lowering hypersaline conditions (Twilley and Day 1999). The hydroperiod affects the productivity and distribution of mangroves, which according to Flores *et al.* (2006) is determined by both the tides and the microtopography. Owing to their nature, mangroves develop best on coastal plains with low topographic gradients. Such areas allow freshwater or seawater to penetrate but also help to determine a flooding gradient which produces a selective response for each mangrove species (Monroy-Torres 2005). This in turn allows for selective mangrove colonization (mangrove zonation). Examples of activities that can hinder mangrove growth include interrupting mangrove irrigation periods, modifying adjacent water salinity, influencing the flooding surface in the rising rivers and altering tide fluctuation by carrying out engineering infrastructure (*e.g.* roads, levees). The effects of such activities can include the reduction in growth and/or development of mangrove zones as well as the potential development of dead mangrove zones. Mangroves of the Northwest have been particularly affected by such hydrologic modifications. New modeling techniques may be used to assist in restoration activities following such occurrences or how they can be used to predict potential impacts to mangroves prior to such constructions by simulating the hydroperiods.

3. TOPOLOBAMPO BAY (THE MARIVI BEACH)

In the 1960's, access to Marivi beach by the inhabitants of Los Mochis and Topolobampo was impeded by the presence of a dense forest of dwarf mangrove and seasonal floodplains. In order to allow easy access, the authorities constructed a road connecting the port of Topolobampo to Marivi Beach. The construction of a 319 m road track sectioned off the El Zacate estuary (see Figure 6). Those responsible for the work left a channel less than 8 meters wide which in fact now connects El Zacate estuary to the main water body. However, this engineering work proved inadequate

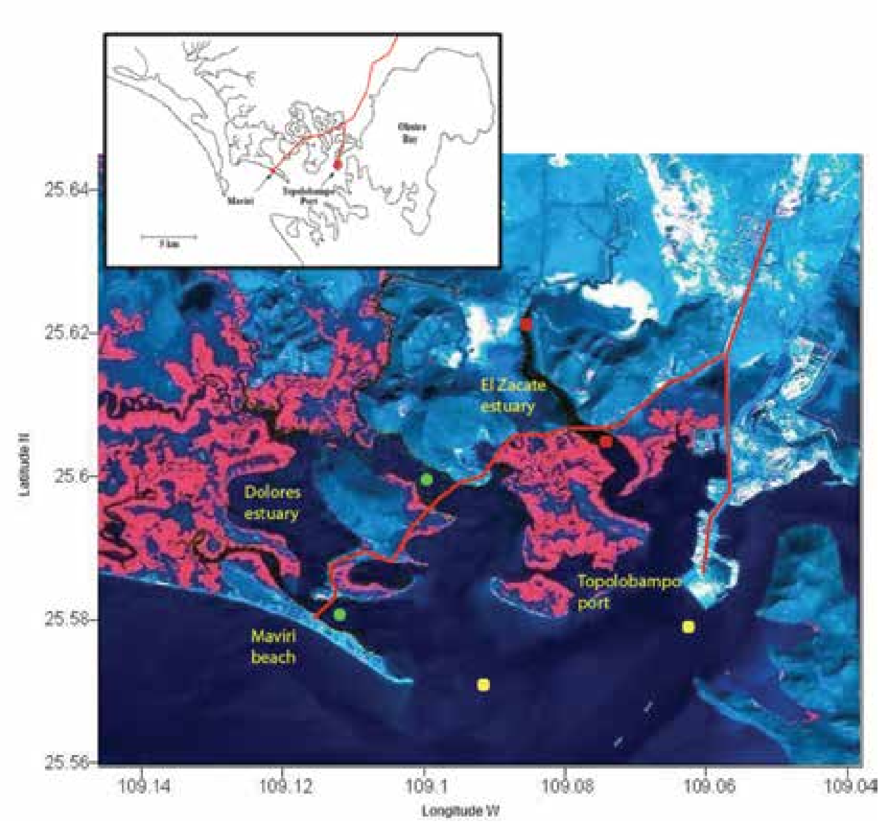


FIGURE 6. Study area. Details of the Topolobampo lagoon, El Zacate and Dolores estuaries. Yellow points represents the sea level measurement sites in the open borders. Red points refer to the internal and external reference points associated to the Zacate estuary. Red line refer the highway and red colour to mangrove areas. The green points refer to the internal and external reference points for the Dolores estuary. The term estuary is translated from the Spanish word "estero" which corresponds predominantly to tidal channels and seasonal floodplains or "marismas" (for location see Figures 1-2).

as it reduced the hydraulic conductivity considerably, resulting in the destruction of about 350 hectares of mangroves.

4. NUMERICAL MODEL

A mathematical model was used to simulate the hydrological conditions of the study zones before and after the hydrological changes caused by human activities. The mathematical model used in these studies was previously applied in other regions such as the Gulf of California (Carbajal and Backhaus 1998) and Santa María del

Oro Lake (Serrano *et al.* 2002). The model is non-linear, with both the equations of momentum and continuity vertically integrated. These equations are solved semi-implicitly, using finite differences in an Arakawa C-grid. The bottom friction is parameterized in an implicit form, and the friction coefficient changes with depth (Baumert and Radach 1992). A complete description of the model can be seen in Carbajal (1993).

The computational grid used to schematize the lagoon systems has a resolution of Δx = Δy = 10 m. The eddy viscosity coefficient was calculated in agreement with Schwiderski (1980). The lagoon systems were forced by the sum of the seven main tide components in the open boundaries. The amplitude and the phase of the seven harmonics were linearly interpolated of the port of Topolobampo the amplitude and phase recorder for this port was used (UNAM 1994).

$$(1)\quad \frac{\partial U}{\partial t}+\frac{U}{(H+\zeta)}\frac{\partial U}{\partial x}+\frac{V}{(H+\zeta)}\frac{\partial U}{\partial y}-fV=-g(H+\zeta)\frac{\partial \zeta}{\partial x}+A_H\nabla_h^2 U-\tau_b^x,$$

$$(2)\quad \frac{\partial V}{\partial t}+\frac{U}{(H+\zeta)}\frac{\partial V}{\partial x}+\frac{V}{(H+\zeta)}\frac{\partial V}{\partial y}+fU=-g(H+\zeta)\frac{\partial \zeta}{\partial y}+A_H\nabla_h^2 V-\tau_b^y,$$

$$(3)\quad \frac{\partial \zeta}{\partial t}+\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0.$$

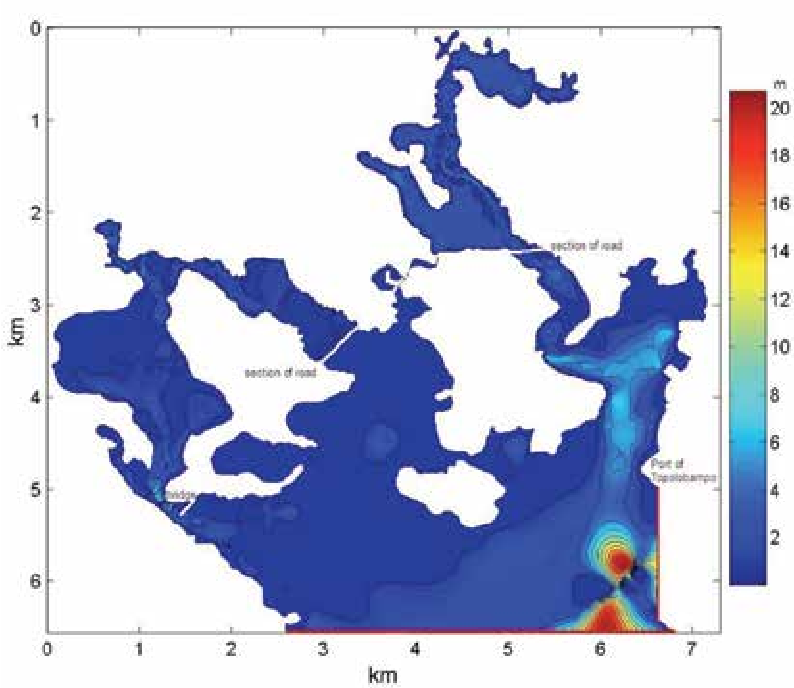
Variables to resolve the elevation of the sea free surface flows ζ and their transport U (in the zonal x direction) and V (in the meridian direction y). H is the depth (bathymetry), t is time, g acceleration due to gravity, A_H horizontal coefficient of turbulent viscosity, ∇_h^2 horizontal laplaciano operator, τ_b bottom friction and f Coriolis parameter.

5. BATHYMETRY

The bathymetric matrix was carried out by capturing about 3,000 sampling points, registering their depth and their geographical position. Measurements in the Maviri zone were carried out by staff from the Topolobampo Oceanographic Research Station of the Mexican Navy. This information was then submitted to MATLAB graphics. A matrix of 658 lines with 731 columns was constructed, with a spatial resolution of $\Delta x = \Delta y = 10$ m, where each node number represented the depth of the study zone (see Figure 7).

6. TIDAL SIMULATION

The open borders (red line, Figure 7) were calibrated to the tides registration of Topolobampo port, Sinaloa, which can be described as a good approximation with the sum of: M_2, S_2, K_1, O_1, N_2, K_2 y P_1. The sea level time-series reproduced in the



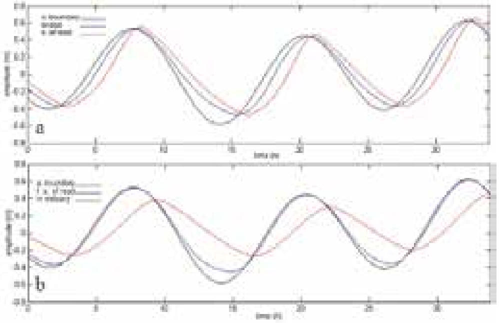


FIGURE 7 (ABOVE). Bathymetry of the study area: Topolobampo-Maviri. Red lines indicate the open borders used for the numerical model. Two meter depth intervals were used. FIGURE 8 (BELOW). A time series of tidal activity under actual conditions (*i.e.* with the highway lanes): (a) Dolores and (b) El Zacate estuaries. Black line is the open border (main water body), blue line outside the estuaries and red line inside the estuaries (see Figure 6).

open borders of the numerical model is shown in Figures 8 and 10 (black lines). This time-series comprises a ~35 hr simulation, within a spring tide time interval reported for Topolobampo Port. The maximum height was 622 mm and the minimum - 580 mm, both referred to as Mean Sea Level (MSL).

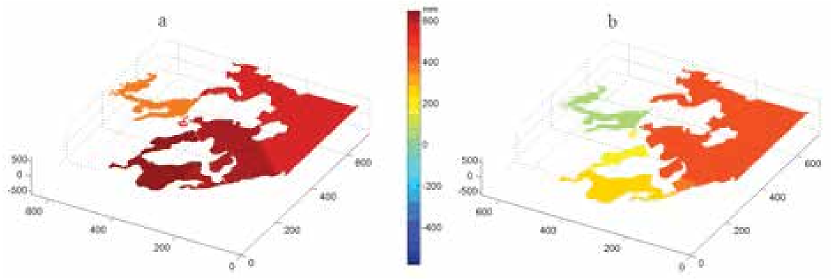
7. ACTUAL CONDITIONS

Real time-series analyses of sea-level conditions (*i.e.* includes highway lanes and bridge) for Dolores estuary are shown in Figure 8a. The black line represents sea level in a point situated in open sea (yellow points, Figure 6); the blue lines show sea level in a point situated in front of the bridge, in the inlet of Dolores estuary (external green point, Figure 6) and the red line refers to the sea level in the point situated in the interior of the estuary, close to the highway lane (internal green point, Figure 6). Three time-series of sea level with actual conditions (*i.e.* includes highway lanes and bridge) for Zacate estuary are shown in Figure 8b. The black line represents the sea level in a point situated in the open sea (yellow point, Figure 6); the blue line shows sea level in a point situated in front of the highway lane which divides the Zacate Estuary (red external point, Figure 6) and the red line, refers to the sea level in a point situated in the interior of the same estuary (internal red point, Figure 6). No significant differences were obtained in the time-series analysis for sea-level in the interior and exterior of Dolores estuary. The registered time-series in the interior of the estuary showed a tidal lag of approximately 20 minutes as well as an increase in height of 23 mm in respect of the series captured opposite the bridge. This result suggests that the tidal flooding zone surrounding the estuary did not appear to be affected, thus sustaining a healthy mangrove ecosystem. Therefore, constructing bridges or placing channels in the highway lane that divides the Dolores estuary are unnecessary.

On the other hand, sea-level time-series in the internal and external points of the Zacate estuary indicate significant differences. The registered time series in the internal points of the estuary shows a tidal lag of approximately 95 minutes as well as a 200 mm reduction in tidal range according to the time registered opposite the highway lane (external point). This result suggests that the tidal flooding zone surrounding Zacate estuary is affected, thus modifying the hydrological conditions of the mangrove. Figure 9 depicts a three-dimensional image of the sea-level elevation in the study zone. The time fluctuations and decrease of the sea-level are considerable in Zacate estuary as compared to the main water body (see Figure 9b).

8. NATURAL CONDITIONS (BEFORE THE HIGHWAY)

So as to understand the hydrological conditions before the highway in the study zone, particularly in the estuaries, the bathymetry matrix was also modified. Specifically, values greater than zero were assigned to the dry points that divide the estuaries (highway lanes). The allocated depth was determined by lineal interpolation on the



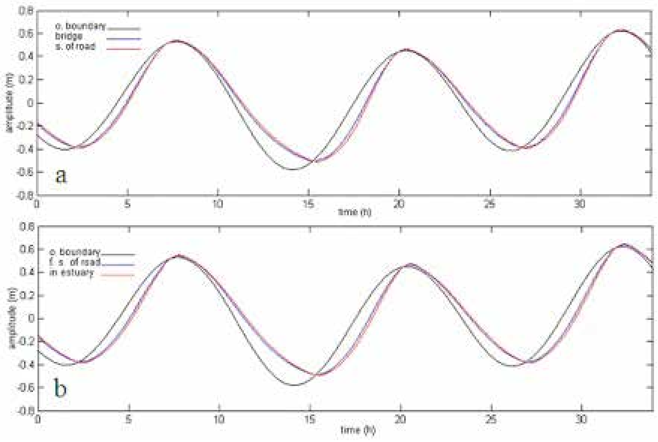


FIGURE 9 (ABOVE). Three-dimensional images of the sea-level fluctuations at Topolobampo-Maviri costal lagoon-mangrove system. El Zacate and Dolores estuaries at high tides (a) and at flow tide (b) for the actual conditions (*i.e.* with highway lanes and bridge). FIGURE 10 (BELOW). A time series of tidal activity under natural conditions (*i.e.* without the highway lanes): (a) Dolores and (b) El Zacate estuaries. Black line is the open border (main water body), blue line outside the estuaries and red line inside the estuaries (Figure 6).

basis of the depth of both sides of the highway lanes. Three time-series at sea-level with "natural" condition (excluding highway lanes) are shown in Figure 10. Likewise, in Figure 8, the black line represents sea-level in a point situated in the open borders; the blue line shows sea-level in a point situated opposite the bridge, in the inlet of Dolores estuary, and the red line refers to sea-level in a point situated in the interior of the estuary, close to where the highway lane was constructed (see Figure 10a). The three points are shown in Figure 6 (green and yellow circles).

The time-series at sea-level with "natural" condition (*i.e.* excluding highway lanes) for Zacate estuary are shown in Figure 10b. The black line represents sea-level in a

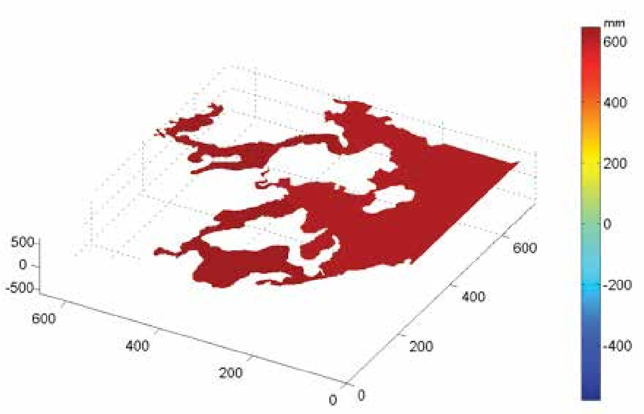


FIGURE 11. Three-dimensional image of the sea-level fluctuations at Topolobampo-Maviri costal lagoon-mangrove system. El Zacate and Dolores estuaries at high tides (a) and at flow tide (b) under "natural" conditions (*i.e.* without highway lanes and bridge). No abnormalities can be seen.

point situated in the eastern open border; the blue line shows sea-level at a point close to where the highway lane was constructed, which divides the Zacate estuary and the red line refers to sea-level in a point situated in the interior of the same estuary. The three points are situated in Figure 6 (red and yellow circles). No significant differences were found in the time-series analysis at sea-level in the interior and exterior of the Dolores and Zacate estuaries. Time-series of the interior of Dolores estuary showed a 2 mm increase in height, however, according to the time-series of the exterior, no important tidal delay was found. On the other hand, the time-series in the interior of Zacate estuary shows an increment of 8 mm in height and a slight tidal lag of less than 1 minute behind the external series. A three-dimensional image of sea-level elevation with natural conditions in the study zone is shown in Figure 11. No significant differences were found for both parameters.

9. RECOMMENDATIONS

The object of implementing a numerical model under natural conditions was to determine the sea-levels in the study zone before the highway lanes were constructed and then to propose the development of new bridges and channels (including dimensions), in a way that the engineering work secures the hydraulic supply (by tides) of the damaged zones. The criteria used for recommending the dimensions of a new bridge in Zacate estuary was to preserve the elevation of the sea level by

TABLE I. Flows, water speed and other parameters for El Zacate on natural conditions, "actual conditions and with the bridge proposal.

	Natural conditions	Actual conditions	Bridge proposal
Depth average	1.73 m	3.3 m	2.7 m
Length	330 m	10 m	70 m
Area	570.9 m^2	33.0 m^2	189.7 m^2
Speed average	0.1687 $m\ s^{-1}$	1.6343 $m\ s^{-1}$	0.5041 $m\ s^{-1}$
Flow	96.31 $m^3\ s^{-1}$	53.93 $m^3\ s^{-1}$	95.63 m3 s^{-1}

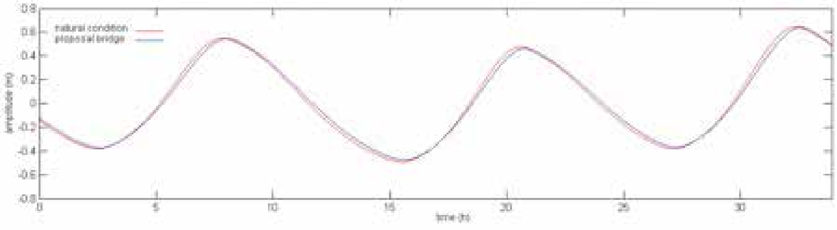


FIGURE 12. A time series of tidal activity under natural conditions (red line) and with the proposed bridge (blue line) in the Zacate estuary.

tides (flooding surface) in accordance to the natural condition. Different numerical experiments were carried out, modifying in each transversal section the proposed bridge (*i.e.* length and depth according to MSL). The numeric model determined that the best solution for Zacate estuary is to construct a bridge measuring 70 m length by 2.7 m depth according to the recommendations of MSL. A time-series at sea-level in the interior of Zacate estuary, with "natural" conditions and with the "construction" of the above described bridge, are shown in Figure 12. Here, the similarity of both series is appreciated. The time-series in the interior of the estuary with the "construction of the bridge" shows a slight decrease in deterioration of less than 5 mm and a slight tidal delay of 14 minutes. On the other hand, the hydraulic conductivity in the entrance of Zacate estuary was calculated under "natural" conditions, actual conditions and the proposed 70 m bridge construction. It should be pointed out that the transversal area was calculated with the actual bathymetry. The results of all three cases are shown in table 1. The results reveal that the proposed bridge project fulfills the conditions similar to natural hydrology before the highway retaining the sea-level at Zacate estuary, with less than 5 mm. The difference in the hydraulic dynamics between natural conditions and the proposed bridge is less than 1%.

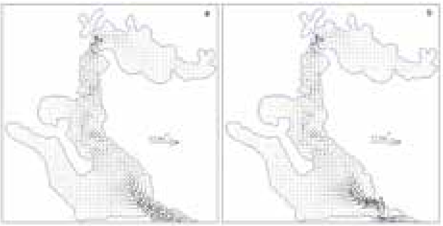


FIGURE 13. Currents distribution and velocities during the flow tide according to the numerical model for El Zacate under natural conditions (a) and with the proposed bridge (b).

The field velocities distribution in the flow tide within Zacate estuary under natural conditions and with the proposed work is shown in Figures 13a and 13b respectively. Both fields have well-known similarities, except in the threshold/entrance/limit of the estuary, which under natural conditions presents a maximum velocity of 57.3 cm s^{-1}, likewise the maximum velocity for the proposed work is 111.2 cm s^{-1}. Then again, we propose that the construction work be carried out between (extreme left of the bridge) at 25 36 23.69" N and 109 04 41.97" W and (extreme right of bridge) 25 36 23.79" N and 109 04 39.46" W, in accordance with the bathymetry and "free" flow. This implicates that the centre of the bridge will be situated at 25 36 23.70 N and 109 04 40.72 W, approximately 20 meters west of the channel.

10. MANGROVE GENETIC CHARACTERIZATION AS A TOOL FOR MANGROVE REFORESTATION

To improve restoration success it is suggested that another technique, related to mangrove genetic characterization be considered. The goal of this mangrove diagnostic is to identify the natural characteristics of the mangrove ecosystem in order to re-establish the damaged areas with the most appropriate mangrove propagules. Before the intensive production of mangrove nursery-reared plants for restoration efforts in Sinaloa, it was deemed important to determine the genetic structure of the four mangrove species naturally distributed in the Northwest of Mexico. The question to resolve was, for the mangrove species, which dispersion via the embryos is influenced by the internal currents of the coastal aquatic systems. Moreover, to present ecological barriers along the latitudinal gradient defined by the geographical position of the aquatic coastal systems of Sinaloa. Without this diagnostic, the empirical restoration efforts could be ecologically dangerous. Specifically, there is the potential, with reforestation efforts, of the presence of the Whalund effect derived from the inbreeding of individuals with a different variance for a number of loci from different populations of a mangrove species. Based on this concern, a genetic structural diagnostic for Sinaloa coast was carried out in 2006 with the collection of samples taken from the 14 principal aquatic coastal lagoons. Microsatellites makers were used of Rosero-Galindo *et al.* (2002) and Nettel *et al.* (2005) which were standardized for Sandoval-Castro (2008) to *Rhizophora mangle* and *Avicennia germinans*. New ones were designed for *Laguncularia racemosa* and *Conocarpus erectus* (Nettel *et al.* 2007, 2008). The seven microsatellites markers used for red mangrove *R. mangle* were: Rm7 [(TA)$_{14}$ (TGTA)$_2$ (CA)$_{11}$ (TA)$_3$ (GA)$_4$ (GA)$_2$]; Rm11 [(CT)$_{16}$ (CA)$_3$]; Rm19 [(AG)$_{26}$]; Rm21 [(CT)$_{12}$]; Rm38 [(CA)$_8$]; Rm41 [(GA)$_{25}$] and; Rm46 [(AT)$_4$ (GCGT)$_8$ (GT)$_8$ (GGAA)$_2$]. For black mangrove *A. germinans* we used seven microsatellites markers: AgT4 [(CATA)$_5$ CATG(CATA)$_9$]; AgT7 [(CAT)$_2$ (AT)$_3$ (GTAT)$_5$]; AgT8 [(TGTA)$_6$]; AgT9 [(CA)$_8$ (GA)$_2$ (CAGA)$_5$]; AgD6 [(ATT)$_4$ N$_7$(GT)$_{15}$]; AgD13 [(CA)$_{10}$] and; CA_002 [(CA)$_{12}$]. The nine new microsatellites markers for white mangrove *L. racemosa* were: Lr101 [(CAAT)$_4$ N$_{36}$ (CT)$_5$]; Lr17 [A$_9$ TAAA (GAAA)$_7$]; Lr22 [(GAGT)$_4$ (GA)$_6$]; Lr33br [(GAAA)$_6$]; Lr38 [A$_4$ G A$_6$ (GAAA)$_7$]; Lr39br [(CTTT)$_5$ N$_6$ T$_6$ C T$_9$]; Lr41 [(CTTT)$_4$]; Lr42 [(CTTT)$_5$] and; Lr8 [(GA)$_{16}$]. Also we develop ten new microsatellites markers for buttonwood mangrove *C. erectus* : Ce21 [(GT)$_{16}$]; Ce25 [(CT)$_{11}$ N$_{24}$ (CT)$_3$ N$_6$ (CT)$_{11}$]; Ce29fa [(CT)$_7$]; Ce32 [(CTT)$_5$]; Ce34 [(CTT)$_8$]; Ce35 [(CTT)$_6$]; Ce42 [(A)$_9$ (GAAA)$_4$]; Ce44 [(CT)$_{11}$]; Ce46 [(CT)$_8$] and; Ce56fa [(AACCG)$_5$].

The initial results of this inventory indicated that, for the State of Sinaloa, the genetic mangrove structure was a distance of less than 300 km. Given this, a sample of 2240 individuals was then taken to then compare amongst the main coastal aquatic systems of the State. The statistical genetic analysis showed two populations of the mangrove species *L. racemosa* and *C. erectus*: the North-Central represented by the systems between Jitzamuri-Bacorehuis and Altata-Ensenada del Pabellon, and the South represented by the systems Huizache-Caimanero and Teacapan-Agua Brava-Marismas Nacionales (see Figure 1: 1-5, 6-7, respectively). For the species *R. mangle* and *A. germinans* three populations were found: North, Central and South. The North population included systems from Jitzamuri-Bacorehuis to San Ignacio-Navachiste-Macapule (see Figure 1: 1-3). The Central population incorporated the systems of Santa Maria la Reforma and Altata-Ensenada Pabellones (see Figure 1: 4-5). The Southern population was represented by Huizache-Caimanero and Teacapan-Agua Brava-Marismas Nacionales (see Figure 1: 6-7). As a consequence of the identification of distinct populations amongst the four mangrove species distributed in Sinaloa, it was dictated by the government that the nursery-reared seedlings must be established in the influence areas of the biological populations and not permitted to be transplanted elsewhere.

Moreover, in 2007–2008 four nursery-reared seedling facilities, two in the North and two in the Central region of Sinaloa, were constructed. The mangrove plant production of these facilities is defined by the biological conditions of the mangrove species found in their local. For these green houses, mangrove plants from *R. mangle* and *A. germinans* are produced in a greater proportion than *L. racemosa* and *C. erectus* species. The reason for the difference is that *R. mangle* and *A. germinans* are the dominant species in Sinaloa and the reforestation efforts need to reflect mangrove forest structure of the natural environment.

The presence of mangrove species populations in Sinaloa provides some evidence of ecological barriers that operate at the species level. Hypothetically, the ecological barriers are represented by the partial independence of the aquatic coastal lagoons systems, but this must be tested. In addition, the North and Central systems are more physiographic limited than the South. Given this physical autonomy, which follows the dominant mangrove species in Sinaloa, it is possible that the South is more closely related to the Nayarit mangrove ecosystem. It is recommended that the genetic approach applied to the Sinaloa mangroves be expanded to other regions of Mexico. In many of these other coastal regions the mangrove restoration activities employ empirical approximation without considering the mangrove species genetic characteristics.

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THE ECOLOGICAL ROLE OF MANGROVES AND ENVIRONMENTAL CONNECTIVITY

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1. INTRODUCTION

Mangroves are one of the most productive ecosystems worldwide and essential to human wellbeing. They provide several services that generate economic benefits for coastal communities (Barbier 2000). Historically, direct users and policy-makers have valued only the short-term, extractive uses which mangroves provide, or have preferred the benefits of a shrimp farm or a resort erected in place of a mangrove forest. Although we know that they are essential from an ecological perspective, few attempts have been made to determine the economic value of healthy mangroves (notable exceptions include Barbier and Strand 1998, and Das and Vincent 2009). We know that mangroves provide feeding, shelter, and growth areas for fish and crustacean juveniles of several commercial species. We also know that many offshore reefs are the adult grounds of these species, where they are fished and generate important sources of income for many coastal towns and cities. But the links between the movements of individuals from coastal habitat nurseries to adult reefs populations have not been well quantified. This has led to a poor understanding of the consequences of mangrove loss in the context of an ongoing trend of decline in fisheries around the world. This trend has been exacerbated in recent decades with the fragmentation and transformation of mangrove forests. Knowledge of the extent of this deterioration is critical to inform prudent policy.

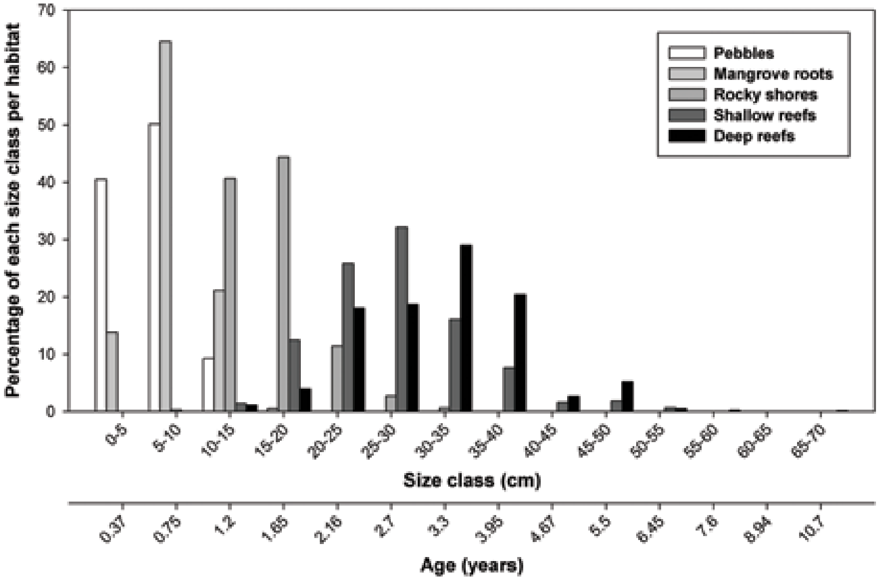

FIGURE 1. Significant differences in size classes ontogenetic patterns of habitat use for the yellow snapper ($X^2 = 8.29, p < 0.01$). Data are percentage of the abundance of each size-class in the underwater surveys per habitat. Age was calculated using von Bertalanffy exponential growth model with age at length zero $t_0 = -0.005$, asymptotic length $L_{inf} = 854$ mm, and growth rate $k = 0.16$.

2. THE LINK BETWEEN MANGROVES AND REEFS

To elucidate these links, we have been studying the yellow snapper, *Lutjanus argentiventris*, in the mangrove forests and rocky reefs of the Gulf of California for more than a decade (Aburto-Oropeza *et al.* 2009). These fishes reach sizes up to 1 m in length, a weight of 10 kilograms, reach maturity after three years, and can live up to 19 years. It is one of the most important commercial species in the southern Gulf and generates more than 3 metric tons of landings per fishing cooperative during spring and summer.

As with many species of the family Lutjanidae, juveniles of yellow snapper are dependent on estuary habitats during their first year of age. After this time, they exhibit marked ontogenetic habitat shifts until adult individuals reach deep rocky habitats (see Figure 1). The life cycle begins with larvae that spend an average of 23 days in the plankton before they recruit in the mouth of the estuaries. Pebble beds are the preferential recruitment habitat in those mouths, where the post-settler individuals of approximately 2 cm in length remain for a couple of months. Individuals

FIGURE 2. Aerial photograph of Balandra Bay showing: pebble beds (blue line), mangrove areas (green lines), and rocky boulders (red lines; photo credit: Michael Calderwood, 2006).

move to mangrove forests for another 10 months, where they find an exceptional nursery habitat provided by the prop roots, mainly of the red mangrove (*Rizhopora mangle*). Juveniles leave mangroves when they reach between 10 and 15 cm in length, and migrate in schools following the rocky shores. When they are still immature (< 3 years old) they live in coastal shallow boulders and shallow rocky reefs. Older mature individuals are present mainly in deep offshore rocky reefs (20 m) and less frequently in seamounts (30 m).

Baja California is the northern limit of mangrove forests in the Eastern Pacific. In this region, mangroves grow under suboptimal conditions and individual plants consist of shrubs or small trees, which form isolated mangrove patches that are surrounded by a relatively narrow fringe of desert vegetation. These spatial conditions allow the establishment of monitoring programs, which can be use to estimate the number of juvenile yellow snappers that arrive and leave the area once the nursery stage finishes. We surveyed one mangrove located 20 km north of La Paz (Balandra, see Figure 2), every four days on average (± 3.2 SD) from February 2005 through May 2006, using snorkeling and standard visual belt transect (Harmelin-Vivien *et al.* 1985). On each visit to Balandra we surveyed the pebble beds and mangrove roots inside the estuary lagoon, and the rocky boulders in the bay. With this important

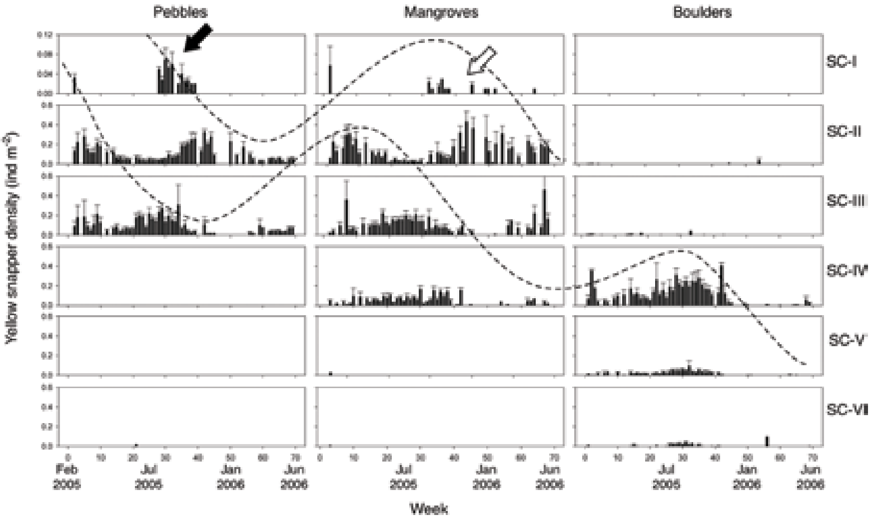

FIGURE 3. Mean and standard error for the six size classes (see Table 1), in the three habitats surveyed in Balandra mangrove (see Figure 2). Note that density scale of SC-I is different from the rest of size classes, in order to show the magnitude of settlement in pebbles (black arrow) and the second settlement pattern occurred in mangroves (white arrow). Dashed line represents the movement of the cohort in time and between habitats.

monitoring effort, we were able to record the last part of the recruitment season of 2004 and the entire recruitment season for 2005–2006 at Balandra (see Figure 3). Recruitment began in the middle of August in pebble beds and continued in the same habitat until the beginning of November. A second smaller settlement started inside mangrove roots at the end of September and continued in the same habitat until the beginning of February 2006. Juveniles grew for 10 months inside mangrove roots, and migratory individuals appeared in the rocky boulders one year later during the summer months of 2006. Using density back-calculated methods (Jones 1984, Pauly 1984), we estimated that the magnitude of the recruitment (individuals < 3 cm) for the cohort 2004 in Balandra was 26,473 individuals (see Table 1). Additionally, we estimated that 13,301 individuals left the mangrove roots to migrate to rocky shores in 2005. The probability of survival for an individual migrating from the mangrove roots to rocky boulders was 64.8%.

The knowledge generated using several studies and the Balandra monitoring program set the basis for a macro-scale estimation of the number of yellow snappers "exported" by the isolated mangrove patches in Baja California. These data are particularly useful because: (1) mangrove patches receive a single cohort of individuals

TABLE 1. Estimates of absolute abundance and survival for juvenile yellow snappers from cohort 2004¬2005, in Balandra mangrove, Gulf of California. Size class I (SC-I), individuals < 3 cm that have just recruited and were recorded mainly in pebbles habitat. SC-II, individuals between 4 and 6 cm that are in transit between pebbles and mangrove roots. SC-III, individuals between 7 and 10 cm, which are the predominant size class living inside mangrove roots. SC-IV, individuals between 10 and 20 cm, which just came out of the estuary lagoon. SC-V, individuals of 25 cm that have reached the 2 years of age. SC-VI, individuals > 30 cm that have reached the maturity.

Category	Upper level size class (cm)	Age (days)	Back-calculation cohort survival	Survivorship schedule *l(x)*	Survival probability *g(x)*
SC-I	3	77	26 473	1.000	0.994
SC-II	6	160	26 302	0.994	0.780
SC-III	10	274	20 518	0.775	0.648
SC-IV	20	589	13 301	0.502	0.132
SC-V	25	765	1 754	0.066	0.168
SC-VI	45	1 657	295	0.011	

every year and patches receive these new settlers during the same peak recruitment months, September and October; (2) juveniles inside mangrove roots are more abundant in the beginning of summer (June to early July); and (3) subtracting the survival rate calculated in Balandra for migrating individuals from mangrove roots to rocky boulders, allows us to accurately estimate the number of individuals that are exported from each of these mangrove patches to the adjacent rocky habitats. In order to calculate the magnitude of this "individual export rate", we need the suitable area for the individual snappers in each mangrove patch. This suitable area is represented by the mangrove-water fringes occupied normally by the red mangrove (*Rhizophora mangle*), because further inland this species is replaced by a mudflat forest dominated by white and black mangroves (*Laguncularia racemosa* and *Avicennia germinans*). These mangrove fringes have different lengths and widths, depending of the geomorphology of the coast. To estimate the length of the mangrove fringe in each mangrove patch, we established that the fringe-to-square root of the total mangrove area ratio is a constant value of 6.13, unrelated to mangrove size or location (Aburto *et al.* 2008). The total area of mangrove for each patch was estimated using polygons obtained using Google Earth software. To estimate the width of the mangrove fringe, we measured different distances from the mangrove in contact with the water to the submerged back forest using Google Earth polygons. Based on the

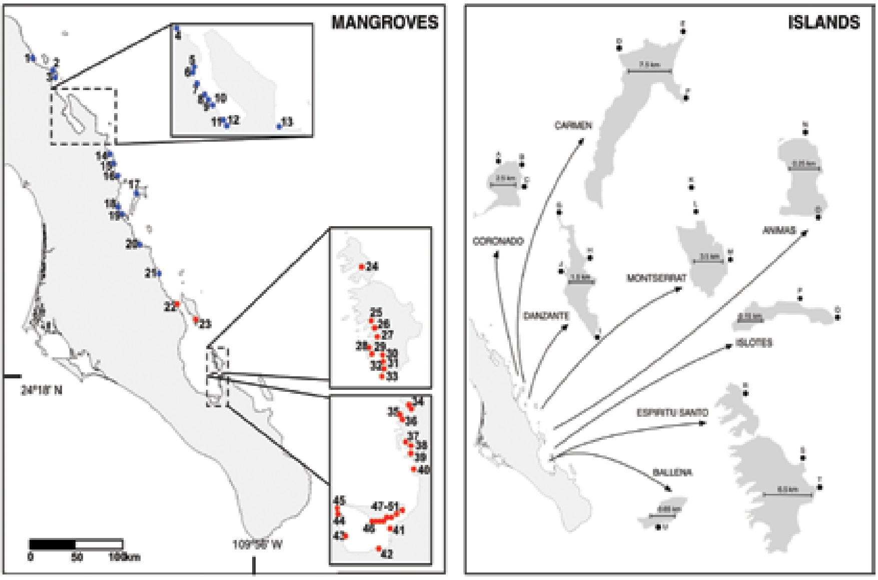

FIGURE 4. Map of the southern part of the Baja California Peninsula showing the location of all mangrove patches sampled in 2007; and the islands that have been monitored since 1998.

size of the mangrove patch, we did several of these measurements covering different widths of the fringe per patch (6.7 measurements ± 0.3 SE). Because it has been shown that physical-chemical conditions change drastically after 40 m from the *Rhizophora* fringe to the inland mudflat (López-Portillo and Ezcurra 1989), and this distance coincides with maximum inner distribution of several species of fish (Vance *et al.* 1996, Rönnbäck *et al.* 1999), we calculated the suitable area for yellow snapper juveniles using the actual average distance calculated in mangroves patches with less than 40 m of fringe width, and a maximum distance of 40 m in the remaining areas. Furthermore, based on their habitat characteristics, we classified the mangrove patches in two groups: Sandy Systems, which include mangrove forests with 100% of the area, inside and adjacent (< 100 m) to the lagoon, with sand habitats; and Rocky Systems, which include mangrove forests with at least 50% of the area, inside and adjacent to lagoon, with rocky habitats.

In June 2007 we carried out visual surveys in 51 mangrove patches (see Figure 4), counting the abundance of yellow snapper juveniles with a total length between 7 and 10 cm. Individuals of this length leave the mangroves approximately two months later. We estimated a total of 135,340 individuals produced by all these mangrove patches for the yellow snapper 2007 cohort (see Table 2). Together, rocky mangroves

TABLE 2. Estimates of abundance of yellow snapper juveniles exported by 51 patches of mangrove forests in the Gulf of California. * Including the survival probability of 0.648 for SC-III size class, using Balandra estimations (see Table 1).

Location	Site	Geographic position		Fringe length (km)	Fringe width (m)		Snappers exported*
		Latitude (N)	Longitude (W)		(average ± SE)		
Central Gulf							
Rocky Mangroves							
4	Mulegé	26°54'04"	111°57'15"	3.468	23.13	(1.82)	7 528.95
18	Nopoló II	25°55'14"	111°20'40"	1.804	39.16	(9.99)	5 510.24
6	Sur Santispac	26°44'36"	111°53'59"	1.371	30.52	(4.88)	2 676.52
8	Buenaventura	26°39'35"	111°50'56"	1.734	21.06	(4.78)	2 184.80
7	Santa Bárbara	26°41'59"	111°52'41"	2.078	10.89	(1.41)	2 022.02
20	San Cosme	25°34'07"	111°09'10"	1.734	17.94	(3.25)	1 617.45
1	San Lucas	27°13'10"	112°12'40"	1.466	19.42	(2.26)	1 526.06
9	El Requesón	26°38'22"	111°50'06"	1.274	17.82	(4.63)	1 430.38
14	San Bacilio	26°21'56"	111°25'58"	1.335	15.59	(1.72)	1 216.78
11	Las Positas	26°32'59"	111°45'43"	1.3	21.77	(7.43)	1 165.50
10	Sur Requesón	26°37'52"	111°48'56"	1.371	14.90	(2.30)	966.53
19	Puerto Escondido	26°48'36"	111°18'13"	1.405	12.87	(1.46)	802.59
5	Santispac	26°45'45"	111°53'29"	0.797	36.70	(7.09)	214.31
15	Punta Mangle	26°16'41"	111°23'32"	0.666	15.02	(3.21)	130.02
Sandy Mangroves							
2	San Marcos	27°07'26"	112°03'15"	2.21	40.00		4 597.22
16	San Bruno	26°13'11"	111°22'49"	2.849	40.00		4 444.39
13	San Idelfonso	26°32'59"	111°32'55"	1.988	40.00		2 843.18
12	Concepción	26°33'47"	111°46'21"	2.875	21.09	(0.59)	1 949.39
3	Los Mojones	27°01'26"	112°00'34"	2.214	17.90	(3.29)	1 610.14

Location	Site	Geographic position		Fringe length (km)	Fringe width (m)		Snappers exported*
		Latitude (N)	Longitude (W)		(average ± SE)		
17	Isla del Carmen	26°01'11"	111°09'48"	1.022	28.09	(7.37)	162.83
Southern Gulf							
Rocky Mangroves							
34	Balandra	24°19'13"	110°19'07"	2.875	40.00		13 705.24
31	San Gabriel I	24°25'31"	110°20'58"	3.13	32.33	(6.09)	11 206.46
38	Bahía Falsa	24°15'40"	110°18'41"	2.033	37.90	(8.62)	8 848.38
32	La Dispensa	24°24'52"	110°20'43"	2.09	40.00		6 112.09
29	El Topo	24°26'14"	110°21'44"	1.622	40.00		5 692.68
40	Enfermería	24°13'54"	110°18'22"	1.502	40.00		2 118.77
35	El Merito I	24°18'06"	110°19'36"	1.734	40.00		2 002.63
36	El Merito II	24°18'18"	110°19'59"	1.062	24.59	(3.62)	1 122.51
22	Nopoló	24°59'46"	110°45'30"	1.009	18.98	(2.48)	622.48
21	Timbabichi	24°16'25"	110°56'20"	1.371	12.35	(1.64)	587.84
Sandy Mangroves							
23	San José	24°53'01"	110°34'26"	6.011	40.00		10 745.49
47	Mogote I-II	24°09'02"	110°21'45"	3.358	40.00		5 528.75
50	Mogote V	24°09'25"	110°20'47"	3.301	40.00		5 149.73
51	Mogote VI	24°09'59"	110°19'56"	2.932	40.00		2 594.54
27	La Gallina	24°27'26"	110°21'18"	2.374	40.00		2 571.94
26	El Gallo	24°28'09"	110°21'28"	2.123	40.00		2 125.62
49	Mogote IV	24°09'15"	110°21'07"	2.732	40.00		1 776.12
24	El Cardonal	24°33'05"	110°22'34"	1.938	40.00		1 680.01
41	El Conchalito	24°08'17"	110°20'51"	2.353	40.00		1 573.04
42	Chametla	24°06'59"	110°20'59"	2.21	40.00		1 358.59
28	Erizoso	24°26'24"	110°22'18"	2.892	36.75	(8.01)	1 036.20
45	Zacatecas	24°10'15"	110°25'58"	2.374	40.00		493.82

Location	Site	Geographic position		Fringe length (km)	Fringe width (m)		Snappers exported*
		Latitude (N)	Longitude (W)		(average ± SE)		
30	San Gabriel II	24°25'58"	110°20'55"	2.294	31.24	(7.80)	465.80
48	Mogote III	24°09'07"	110°21'30"	2.349	40.00		457.99
46	La Punta	24°08'59"	110°22'38"	1.938	40.00		332.64
43	CIB	24°07'51"	110°25'10"	0.05	35.40	(2.62)	292.36
44	Centenario	24°09'49"	110°25'37"	1.622	27.34	(5.24)	223.71
39	Puerto Gata	24°14'53"	110°18'51"	1.371	40.00		218.37
33	Las Navajas	24°24'11"	110°20'51"	1.734	28.286	(8.12)	63.76
25	La Ballena	24°28'47"	110°22'01"	1.062	33.14	(5.58)	19.61
37	UABCS	24°16'13"	110°19'26"	0.867	28.65	(5.21)	13.21

contributed 60% of the juveniles, although they represent only 31% of the suitable area estimated. The mangrove patches located in the southern Gulf represented 74% of the productive area calculated, and they contributed 67% of the individuals exported to rocky reefs in the study region. We estimated a juvenile yellow snapper density export rate of 15,000 fish per km^2, corresponding to the less productive sandy systems, to 76,000 fish per km^2 from rocky systems located in the southern region of the Peninsula. Although juvenile growth and mortality rates can be relatively similar among estuaries (Kramer 1991), changes in growth and mortality can affect the total number of individuals exported. This is a pertinent consideration because we calculated survival rates using only data from a rocky mangrove (Balandra). For example, a decrease of 10% in the survival probability of individuals coming from sandy systems would represent a 5% decrease in the overall number of individuals exported.

Every year these isolated mangrove patches send different amounts of young yellow snapper to the offshore adult grounds, as we estimated in 2007. Unfortunately, it is extremely difficult to have direct evidence of the movement of these individuals from the mangroves to offshore reefs, since tagging and finding them again requires a colossal effort. However, we have been surveying 21 reefs in 8 offshore islands (see

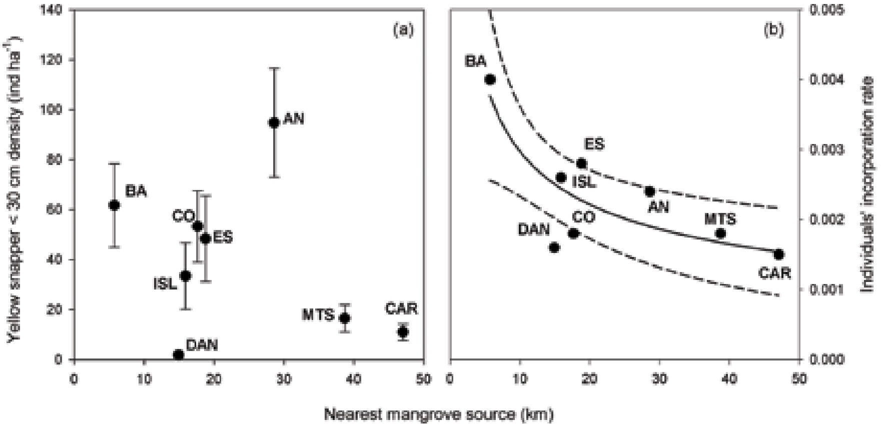

FIGURE 5. (a) Relationship between distance to the nearest mangrove source and the density of juvenile yellow snappers (*Lutjanus argentiventris*). Islands with a mangrove source less than 20 km away had on average, more than 40 individuals per hectare while islands with a mangrove source farther than 30 km (MTS and CA), averaged less than 20 individuals per hectare. (b) Relationship between nearest distance to mangrove and the recruitment rate of immature (< 30 cm long) yellow snappers. The size corresponds to migratory sub-adults that have recently emigrated from their mangrove "nurse"patches. In both plots, island names are shortened as follows: AN = Ánimas; BA = Ballena; CA = Carmen; CO = Coronado; DAN = Danzante; ES = Espíritu Santo; ISL = Islotes; MTS = Montserrat.

Figure 4), since 1998. Every September we visit each of these reefs. With SCUBA diving and standard visual census methodologies (Harmelin-Vivien *et al.* 1985), we count and estimate the size of yellow snappers, using five transects of 250 m^2 each one and with PVC plastic tubes that have 5 cm size intervals marked on. Together with life history variables of the species and virtual population analyses, we use size-frequency distributions to calculate the incorporation rate of each size class in each island.

We hypothesized that the yellow snapper's grounds on offshore islands receive the immature individuals (< 30 cm), "exported" by the mangrove patches, in proportion to the distance between these grounds and mangrove sources. This incorporation rate of young individuals to the islands followed a negative exponential pattern ($r^2 = 0.64$, $\mathcal{F} = 10.87$, $p < 0.05$), as the distance between the island and a mangrove source increased (see Figure 5). There were significant inter-annual variations in the density of these immature individuals between islands (two way ANOVA $\mathcal{F} = 1.48$, d.f. = 63, $p = 0.016$). On average, islands with a mangrove source less than 20 km distant had more than 40 individuals per hectare; while islands with a mangrove source farther than 30 km, averaged less than 20 individuals per hectare.

3. ECONOMIC ACTIVITIES AND THEIR CONNECTIONS WITH MANGROVES

As mentioned previously, there are numerous economic benefits provided by mangroves and informed policy decisions require rigorous estimation of these benefits. This is particularly problematic for policy makers; the benefits of mangroves are often diffuse; they are typically not traded in any market and are often ignored in the policy making process. This is not the case for replacement values such as shrimp farming or resorts. On the contrary, the replacement values of areas that are developed are easily estimated and form the focus of policy debates (Sanchirico and Mumby 2009). The importance of this point is highlighted by recent work documenting the transformation of coastal lagoons for urban development in northwest Mexico (Ruiz-Luna and Berlanga-Robles 2003). The myriad benefits of the mangroves in Mexico and particularly in the Gulf of California are not well quantified, and there are few studies quantifying the economic benefits provided by these ecosystems in this region (but see Barbier and Strand, 1998, for Campeche, in the Gulf of Mexico).

3.1. Fishery benefits of mangroves

Understanding the functional role that mangroves play in replenishing populations is critically important for the proper management of coastal development and economic activities, such as the fisheries. With our studies on yellow snapper, we have found that the abundance of juveniles is linearly related to the nursery suitable area provided by the red mangrove fringe. Southern rocky systems ($y = 291.02x - 141.46$; $r^2 = 0.66, p = 0.025$) can contribute five times more yellow snappers per unit area than southern sandy systems ($y = 61.24x - 116.13$; $r^2 = 0.52, p < 0.01$); although, central rocky systems ($y = 232.60x + 52.83$; $r^2 = 0.81, p < 0.01$) only contribute 1.5 more individuals per unit area than central sandy systems ($y = 129.39x - 117.30$; $r^2 = 0.65, p = 0.1$).

This linear relationship between the edge of the mangrove forest fringe and the abundance of individuals opened the possibility to analyze the relationship between the cover of mangrove areas and the amount of fisheries landings that are generated in several regions. In order to evaluate these ecological services provided by mangroves for local fisheries, we recently published a study using landing records from local offices of the Mexican National Fisheries and Aquaculture Commission and wetlands data for northern Mexico (see Aburto *et al.* 2008). Using regression analysis, we fitted these landings data for blue crabs and mangrove-related commercial fish (snappers, mullets, snooks, and other fisheries with similar life cycles) in 13 coastal regions around the Gulf of California, against the total area of mangrove forests in the lagoons within a 50-mile radius of the port where the landings were recorded. The results showed a very high correlation between fringe mangrove habitat and fish yield: the larger the length of fringe mangrove, the higher the landings recorded ($r^2 = 0.76$, $p < 0.0001$).

Every year, mangroves in the Gulf of California produce an average of 11,600 tons of these mangrove-dependent fisheries that generate an annual income of 19 million U.S. dollars for local fishers at the ex-vessel (or in-the-fishing-ground) prices. We estimated that the marginal productivity of 1 km of fringe forest is around US $37,500 produced in landings. More importantly, if we assume that each kilometer of fringe represents one hectare of suitable mangrove area for fisheries and discount the lost fisheries over a period of 30 years (the time frame of a human generation), the present gross value (using a 5% discount rate) of one hectare of mangrove fringe for the local economy is around US $605,000. This last value is two orders of magnitude higher than the US $800 per hectare value set for Mexico by current legislation based on the cost of mangrove replanting in 2006.

3.2. Other benefits of mangroves in the Gulf of California

The study above highlights the fundamental contribution of mangroves to local fishery-based economic activity, but there are many other benefits that should be quantified in future research, including the sustainable flows of benefits from healthy mangrove systems such as water filtration and coastal protection against storm surges.

Economists typically classify the benefits of a natural system such as mangroves into three main groups: use values, indirect-use values and non-use values. Use values include all values that involve the user physically interacting with the natural system; for mangroves this category includes activities such as harvesting lumber or enjoying recreational activities in the mangrove. Indirect-use values involve the ecological functions and services of a natural system. Examples of indirect-use values of mangroves include the nursery values discussed previously as well as water filtration and flood or storm protection for nearby residents and structures. Indirect-use values are often important flows of benefits provided by natural systems but are not always easy to estimate and may require a large quantity of economic, biological, physical and chemical data. Non-use or passive-use values are benefits derived without any physical interaction with the environment. Existence value is one type non-use value and it is an attempt to describe the benefits individuals receive simply from the knowledge that a natural system exists in some particular state. Non-use values are almost always estimated from stated-preference survey data.

Mangrove benefits can also be categorized by their sustainability. Some benefits enjoyed today may reduce the available benefits in the future, or cause the value

TABLE 3. Categories of benefits expected from Gulf of California mangroves (after Barbier 2000).

	Non-depreciating flows	Potentially depreciating flows	Replacement values
Market prices only			Use values: · Aquaculture · Hotel/resort
Market data, surveys and physical and biological data	*Indirect-use values:* · Fish nursery · Bird habitat · Erosion control · Flood/Storm protection	*Use values:* · Charcoal · Lumber · Fish/Meat · Medicine *Indirect-use values:* · Water filtration	
Surveys/Consumer data only	*Non-use values:* · Existence · Bequest	*Use values:* · Recreation	

of mangrove natural capital to depreciate. Examples of this category of benefits, documented by Kovacs (1999) for Nayarit and Sinaloa include charcoal and lumber production primarily from *Rhizophora mangle*. Excessive use of this species for charcoal and lumber may lead to a reduction in the nursery benefits of the fringe habitat documented above. Although it is possible to produce sustainable harvests of mangrove lumber, it is also possible to over-harvest and decrease the functional value of the mangroves for the provision of other ecological services, including future lumber availability. Other benefits cause no depreciation in the value of mangrove natural capital as the service is provided. These include many of the functional values such as habitat or nursery services. In the opposite extreme are the replacement values of mangroves. These values involve the partial or complete destruction of mangroves for shrimp farms, tourism, or urban development (see Table 3).

There are several methodologies available to estimate the values in Table 3. A review of methods using survey data or other consumer behavior data to estimate these values is available in Champ *et al.* (2003). The fish-nursery results in the previous section are an example of production function methods. As in the fishery benefits study, the goal of any production function method is to determine the economic value of the increased quantity or quality of output caused by the function of the natural system. These methods are very straightforward economics but the data requirement for many indirect-use values can be quite large. For example, to determine the value of water filtration services, the researcher must learn the rates of filtration for each relevant substance, the functional importance of clean water in downstream ecosystems and the willingness-to-pay by user groups or the cost of a replacement technology. Valuation of this type has not been done in the Gulf of California and is a research priority.

There has been some qualitative work in Mexico confirming the existence of a number of the above values to locals. Kovacs (1999) found locals in Nayarit and Sinaloa are familiar with numerous benefits of mangroves and were able to "readily distinguish the four species." Interviewees claimed that at least one species was good for construction, fuel, medicine or tannins (all depreciating values). Interviewees recount using *Rhizophora mangle* lumber "often", for trellises for tobacco crops, walls/fences, stakes, posts, beams, and fishing *tapos*. In a later study (Kovacs *et al.* 2004), local fishermen in the same region were found to have an accurate understanding of the hurricane impacts on mangroves, highlighting the importance of mangroves to the fishing industry. In a detailed regional study interviewing fishers along both coasts of the Gulf of California, López-Medellín *et al.* (2011) found that fishermen in the region generally acknowledge that mangroves sustain fisheries and biodiversity and that, secondarily, they provide aesthetic values that attract tourism. Furthermore, most fishermen reported a diverse combination of multiple direct uses, including firewood, medicine, tannins, construction lumber, and wood for harpoons and fishing gear. Finally, they recognized the presence of growing threats to the mangrove ecosystem, including land-clearing for aquaculture, industrial and urban pollution, construction for new developments, agricultural drainage, and the growth of tourism and urban complexes.

Elsewhere in Mexico, Kaplowitz (2000) found that residents near the Chelem lagoon in northern Yucatan perceive mangroves to provide extractive benefits as a source of snails, crabs, finfish, salt, and shrimp. More intriguingly, and opening ground for future work, Kaplowitz found that 100% of respondents in his focus groups independently suggested "beauty" as an important mangrove value. This motivates future survey work to quantify the aesthetic or existence value associated with mangroves in the Gulf of California. These values can be estimated using contingent valuation and other stated preference methods to determine the willingness of locals to pay for conservation of the mangroves. A complementary approach applied to mangroves in India by Stone *et al.* (2008) involves surveys of willingness to contribute labor time to restoration and conservation efforts.

Near-term research in the Gulf of California can focus on water filtration and storm protection values provided by mangroves. Also, agricultural expansion in the region may require the protection of mangroves to absorb the associated nutrient and pesticide loads. In order to quantify these regional benefits, it is necessary to work at the regional watershed scale. The data may include local agricultural activities, mangrove cover and composition, water quality, storm-related property damages, and population census data. As mentioned above, there may be significant household-level use-values associated with mangroves as well as aesthetic and non-use values. It is important to develop household surveys to be applied to local residents in the major regional watersheds to quantify these benefits to local communities.

A recent study (Rubio-Cisneros *et al.* 2014) assessed the transnational ecosystem services provided by winter habitat for waterfowl in coastal lagoons in the Gulf of California for the hunting industry supported by these birds in the United States. The study showed that the number of waterfowl harvested in the United States is related to the abundance of waterfowl wintering in Mexico, and that, on average, this cross-border flow of ecosystem services annually yields US $4.68 million in hunting stamp sales in the western United States, plus an estimated US $3–6 million in consumer surplus produced in addition to governmental stamp sales revenue, demonstrating that conservation efforts in western Mexico that can result in transnational benefits received in the United States

The ultimate goal of this economic research is to inform proper management of mangrove resources; it is not yet knowing the specifics of local and regional *de jure* or *de facto* management regimes for mangrove forests. In the course of data collection and field work in the watersheds, learning more about local laws and customs governing the usage of mangrove forests is expected. Identifying the aspects of management leading to improved outcomes for local residents is a priority in the regional research and a necessity to deal with the many stressors on mangrove systems described below.

4. THE REGIONAL DRIVERS OF MANGROVE LOSS IN THE GULF OF CALIFORNIA

In the Gulf of California mangroves vary from extensive and dense forests in Sinaloa and Nayarit, to small and scattered mangrove patches in their northern distributional boundary in Sonora and Baja California. In this region, mangroves occupy approximately 208,110 hectares in costal lagoons, small bays, and inlets, both along the mains coasts and in some of the regional islands. In the last two decades the Gulf of California is one of the areas of Mexico where the biggest changes are happening concerning the transformation of mangrove ecosystems. The main effects over this ecosystem have been well identified in many sources, but their magnitude and repercussions at a regional scale and their dynamics are barely understood.

Although mangroves are federal property, many economic activities have started to develop around mangroves. The growth of coastal cities, new coastal developments, and the growing regional demand for homes, food, and services has impacted mangroves in the region. The population of the northwestern coastal part of México grew from half of million in 1950, to more than 5 million inhabitants in the year 2000, concentrated mainly in 18 cities. As a result of the concessions granted by the federal government, important industries such as agriculture, shrimp farming, hotels, marinas, and salt ponds have exponentially developed around mangroves.

The way mangrove areas are affected by these activities in the Gulf is different from one coast to the other: on the mainland coast (Sonora, Sinaloa, and Nayarit), agriculture and shrimp farming have driven the change in mangrove coverage; on the peninsular coast (Baja California Sur), tourism industry and urban developments have propelled the changes. Almost 90% of all mangrove areas in the Gulf of California have some degree of impact. Although the effluents from shrimp farming and sewage from city wastes are, jointly, not close as harmful as agricultural drainage (see description below), the most impacted systems are those located either near large agricultural zones, coastal cities, or shrimp farms in the Gulf's mainland, or cities with an important tourism infrastructure in the Peninsula.

To support the rising agricultural production in the Gulf's mainland coast, dams have been built during the last century stopping natural water flow towards the coastal lagoons and diverting it towards irrigation projects. In addition, the leachates of agricultural drainage are collected in the large irrigation districts and discharged in the coastal wetlands through drainage canals. Discharges from shrimp farming and urban sewage further increase the nutrient and organic waste load dumped into mangrove areas, pushing the nutrient filtration carrying capacity of the system to its limit. Nutrient enrichment favors growth of shoots relative to roots, thus enhancing growth rates but increasing vulnerability to environmental stresses that adversely affect plant water relations (Lovelock *et al.* 2009).

In the Peninsula, population growth along with touristic development such as hotels, marinas, and resorts directly affects the conservation of mangroves patches. In many areas, such as the Nopoló estuary south of Loreto and El Mogote sand bar in front of La Paz, these developments have been destroyed entire patches, while many other patches face unstable estuarine conditions due to modifications in hydrologic conditions such as salinity, currents, and/or water levels, as a result of the establishment of roads, bridges, and home structures.

Water quality in mangrove lagoons is an important and not well-studied subject in the region. Two major concerns about this topic are pesticides and nutrient overload from agricultural runoff, and raw municipal discharges from human developments. With approximately five million hectares of irrigated lands, the valleys of Mexicali, Yaqui, Mayo, Fuerte, and Culiacán, represent 15% of the terrestrial surface of the coastal region of the Gulf of California and are the most productive crop growing zones in Mexico. These valleys, which mainly produce wheat, corn, rice, soy, sugarcane, and vegetables, generate 53.7% of the total phosphorus and 33.3% of the total nitrogen discarded into the regional coastal lagoons. The cities that surround the Gulf of California, few of which have sewage treatment plants and which occupy only 0.32% of the regional area, contribute with 3.6% and 4.1% of the phosphorus and nitrogen loads, jointly discharging around 2,000 tons of P and 5,500 tons of N every year into the Gulf of California.

Shrimp farming, which has had an exponential growth in the last decades, is the activity that produces another source of nutrient enrichment impact for mangrove areas. Of the 335,000 hectares of coastal lands land with potential for shrimp farming development in Mexico, 70% (236,000 ha) lie the Gulf of California. In 1995, a total extension of shrimp farming ponds of 26,000 ha was reported. By 2002 the Mexican federal dependencies of fisheries and aquaculture (CONAPESCA and SAGARPA), reported that the total area of shrimp farming was 52,648 ha, 97% of which (51,059 ha) were located around the Gulf of California in the following order: Sinaloa 37,390 ha, Sonora 9,951 ha, Nayarit 3,400 ha, Baja California 190 ha, and Baja California Sur 128 ha. In only seven years, shrimp farming duplicated its areal extent around the Gulf, expanding at an annual rate of 10%, or *ca.* 3,800 ha per year. The more common management system in the region is the semi-intensive type that occurs in 89% of the farms; the intensive and extensive types comprise 2% and 9%, respectively.

In the last decade of the 20th century, the *ejidatarios* started shrimp farms projects in the area. It was not until 1992, after the privatization of *ejido* lands in the Mexican Constitution, that the rapid development of this activity took off. The farms are built in coastal saline flats surrounded by mangroves, rather than within the mangroves themselves, because pond construction and management are easier on flat land than in the mangrove mudflat. This design, which is used in the entire Gulf, brings indirect impacts such as altered hydrological patterns, hypersalinity and eutrophication to the mangrove systems. Shrimp ponds, roads, and levees in the mangrove hinterland reduce the hydrological flux towards the intertidal zone. Furthermore the seawater pumped into the shrimp ponds induces seawater penetration inland, increasing substrate salinity at the back of the mangrove and modifying the forest species structure and composition. For example, in the Teacapán-Agua Brava system, the opening of the Cuautla channel killed 18% of the mangrove, and, 13 years later, new patches of *Rhizophora mangle* appeared in the destroyed area but not of the other mangrove species. At the end the total extent of mangrove forest loss as a result of the Cuautla project turned out to be only 3% of the initial mangrove extent, but the original system changed completely. Therefore, when natural or anthropogenic phenomena alter the natural condition of the forest, the many services provided by the system are partially or totally altered as well. These alterations have both direct and indirect effect on coastal ecosystems that receive cumulative impacts from the whole watershed.

According to Robertson and Phillips (1995), between 2 and 3 ha of red mangrove (*Rhizophora mangle*) are required to treat the wastes produced by a semi-intensive shrimp-farming hectare, and 22 ha to treat the effluents of each hectare of intensive farming. Considering a scenario with approximately 51,000 ha of shrimp ponds in operation for the entire region around the Gulf of California, we can estimate that the annual load of N and P is 5,700 tons and 1,600 tons respectively. These values are very similar to the municipal discharge, but less significant than the agricultural load. With these approximations, and considering that each hectare of mangrove forest can tolerate sustained inputs of 300 kg N and 30 kg P annually (Páez Osuna *et al.* 2003), between 18,950 and 54,426 ha of healthy mangroves would be needed to process the wastewaters of shrimp farms. However the location of most shrimp farms in Baja California Sur, Sonora and Sinaloa does not match the distribution of mangrove areas (Páez-Osuna, 1999). The largest mangrove area in the Gulf of California is in the estuarine system of Teacapán-Agua Brava, in Marismas Nacionales, which harbors 113,238 ha of mangrove forest in the north part of the state of Nayarit and in the south of Sinaloa. Nevertheless, this area has only 3,400 ha of shrimp farming ponds that represent only 10% of Sinaloa's shrimp farm extension.

At regional or local scale, the biggest human impacts over the hydrologic systems are caused by the change of land use and especially by the transformation of natural ecosystems to agricultural or suburban areas. This transformation has generated an increase of 220% in runoff waters reaching the coastal lagoons, increasing the anthropogenic nutrient load in and around mangrove ecosystems. Aquaculture, in the way it is currently done, pumps coastal seawater, filled with crustacean larvae and small fish, into the ponds and competes for the resources of coastal aquatic ecosystems. Together with the agricultural discharges, aquaculture wastewaters saturate coastal waters with excess nutrients and their flow often modifies the adjacent lagoon system. Shrimp farms in the Gulf of California add stress to mangroves because of the nutrient saturation of estuarine systems, while changes in lands use, due to tourism and urban developments, change the hydrologic patterns and the connectivity between the terrestrial and the aquatic system.

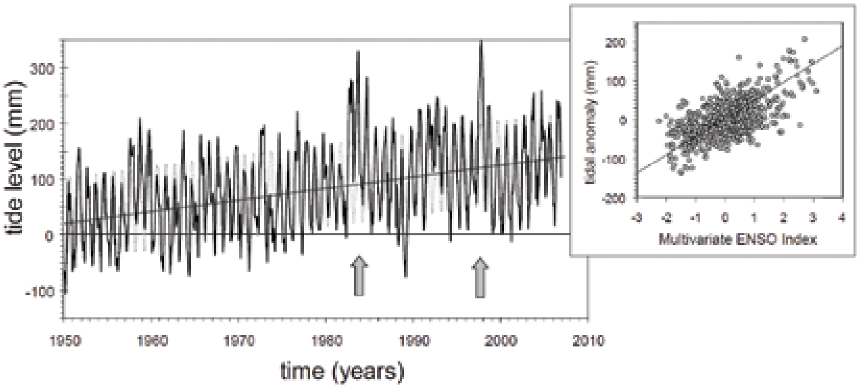

FIGURE 6. Monthly mean sea-level values for the Pacific coast of Baja California. The data line in black shows the averaged values of the three tide stations (Scripps, San Diego, and Los Cabos), arbitrarily taking the mean tidal level for year 1950 as the baseline origin. The straight line in gray indicates the general trend for sea-level rise, the sinusoidal broken line in the back shows the harmonic function describing seasonal variation. The deviations from these two predictors, shown in the insert at the right, were highly correlated with the Multivariate ENSO Index, a measure of oceanographic conditions in the Pacific Ocean (see Table 2 for significances). The vertical arrows show the El Niño years of 1982 and 1997, when the tidal anomaly reached extremely high values, *ca.* 20 cm above the predicted trend, flooding large expanses of the desert coastal saltflats.

5. CLIMATE CHANGE AND MANGROVES

Pressure on mangroves will increase as local communities continue to grow. Apart from the changes brought by local disturbances, mangroves are in the forefront of anthropogenic sea-level rise and oceanographic anomalies that occur as a result of rising global temperatures. In the Gulf of California, mean tidal levels have been increasing during the last century at a fixed background rate of 2 mm per year (see Figure 6). This value is compounded by the occurrence of ENSO (El Niño Southern Oscillation) conditions, a time in which warm waters accumulate in the eastern Pacific Ocean and further elevate sea-levels due to thermal expansion of the warm upper ocean layers.

5.1. Mangroves and sea-level rise

Rising sea levels put growing pressures on coastal lagoons; they tend to erode the mangrove fringes and flood previously dry salt-flats, effectively pushing mangroves inland. On a background of rising sea levels, extraordinary warm-phase oceanic anomalies and unusually strong hurricanes can set the stage for sea-level rise to drive rapid changes in coastal landforms delivering a combination knockback to coastal ecosystems (López-Medellín *et al.* 2011). Despite the fact that sea-level rise operates at a constant level, and is expected to increase to 2.5–3.0 mm per year during the 21st century, the inland expansion of mangroves progresses in pulses, driven by the warm phase of the ENSO anomaly that can episodically add 20 cm or more to the background trend for sea-level rise. During the strong ENSO seasons of 1982–1983 and 1997–1998, for example, the salt flats in Magdalena Bay became regularly flooded with the high tides and mangrove establishment followed. After the ENSO anomalies passed, continuous sea-level rise, on the other hand, kept these mudflats wetter than they were before, allowing the newly established seedlings to survive, while, at the same time, a significant amount of mangrove fringe in the front of the lagoon was lost as a result of increasingly erosive ocean dynamics (see Figure 7).

The inland expansion of mangroves as a result of rising sea-levels highlights the importance of mangroves as "healers" of the coastline as sea-level rise progresses, and the pivotal role they will have in decades to come. This important environmental service, however, does not ease concerns for the conservation of coastal lagoons. Ecologically, an area occupied by new-growth mangrove saplings does not have the complexity of an old-growth fringe stand, which provides very valuable environmental services such as fisheries or coastal protection (Barbier *et al.* 2008, Aburto-Oropeza *et al.* 2008).

5.2. Mangroves as carbon sinks

Existing data indicate that mangroves are among the most carbon-rich forests in the tropics, containing on average 1,023 tons of carbon per hectare (Donato *et al.* 2011). Organic-rich, peaty soils can range from 1 m to more than 3m in depth and accounted for most of the permanent carbon storage in mangrove systems. This information, adds an additional element of concern around the destruction of coastal lagoons: globally, it is estimated that mangrove deforestation generates emissions of 20–120 million tons of carbon per year —as much as around 10% of emissions from deforestation globally, despite accounting for just 0.7% of tropical forest area lost (Donato *et al.* 2011). Despite the general information that exists, worldwide, on the importance of belowground carbon sequestration in mangroves, very little is known about the formation of mangrove peat in Baja California. Because of the growing importance of carbon storage and carbon sequestration in our current context of accelerated increase of atmospheric CO_2, the subject is of great importance for future research.

Much more is known in the Gulf of California about above-ground productivity and carbon fixation. Mangroves reach their northernmost distribution in the Gulf's

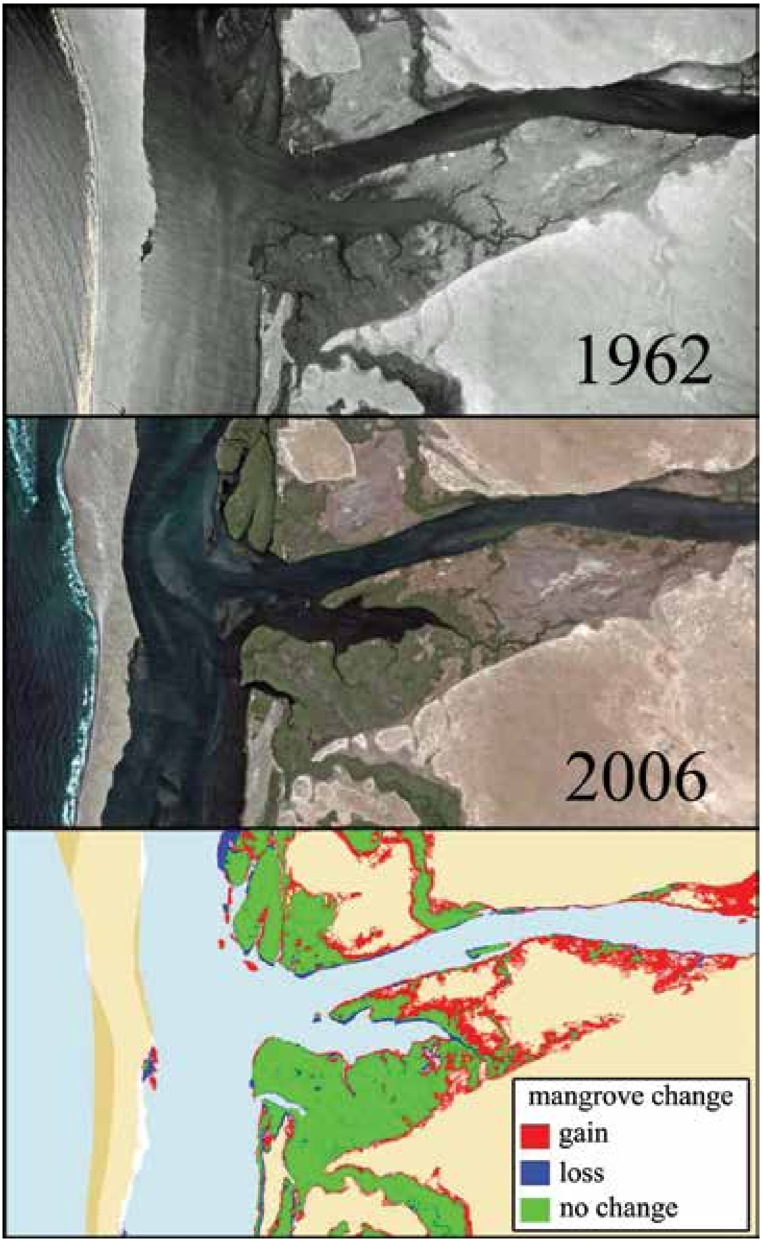

FIGURE 7. The effects of sea level rise are visible from above in Boca de Santo Domingo, Bahía Magdalena: The top plate shows an aerial photograph taken in 1962, the middle one, a GoogleEarth image from August 2006. The image at the bottom highlights the differences between the two timed photos. With rising sea levels, mangroves have grown inland occupying the desert saltflats (red), while the mangrove fringe in the water front has died back.

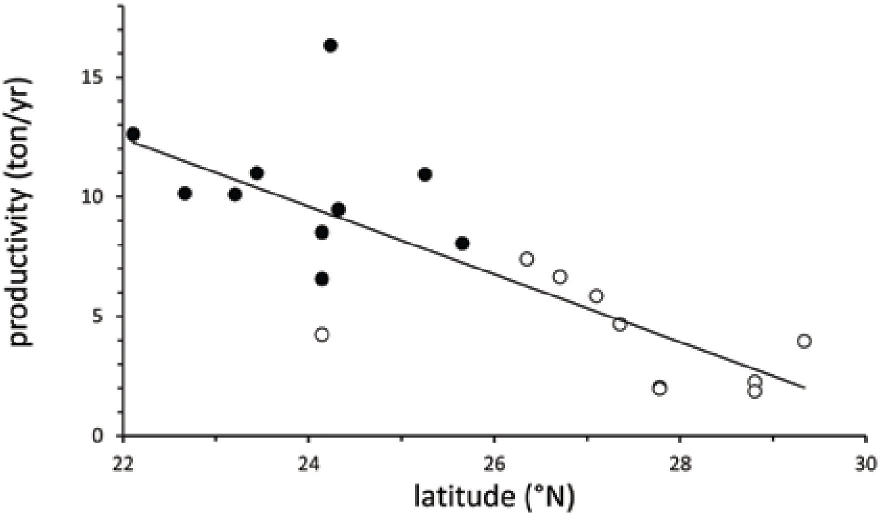

FIGURE 8. Relationship between latitude and productivity in mangroves around the Gulf of California, in northwestern Mexico. Open dots, mangroves with *Rhizophora mangle*, black dots mangroves with *Avicennia germinans* and/or *Laguncularia racemosa* ($r^2 = 0.62, p < 0.0001$).

Midriff, where they grow stunted and under sub-optimal conditions. Nevertheless, they maintain high litter-fall rates throughout their range, exporting organic material to surrounding lagoon areas with important ecological and economic implications. In a recent meta-analysis study (López-Medellín and Ezcurra 2012), we found that mangrove litter-fall in the Gulf is strongly associated with latitude. The fringe mangrove *Rhizophora mangle* showed the highest productivity. In the southernmost coasts of the region, in Marismas Nacionales, annual above-ground litter-fall is near 15 ton ha^{-1} yr^{-1}, and it decreases gradually northwards, reaching values of 2–4 ton ha^{-1} yr^{-1} in the edge of their northern distribution, in the Gulf's Midriff (see Figure 8). The capacity of mangroves to produce high amounts of organic matter contrasts with that of their surrounding ecosystems: north of latitude 25°, along the coasts of the Sonoran Desert, mean mangrove litter production is 4 ton ha^{-1} yr^{-1}, while that of the surrounding desert is less than 1 ton ha^{-1} yr^{-1}. South of latitude 25°, along the coasts of Sinaloa and southern Baja California, mean man- grove litter production is 9.8 ton ha^{-1} yr^{-1}, while that of the nearby thornscrubs is less than 4 ton ha^{-1} yr^{-1} (López-Medellín and Ezcurra 2012, and references therein). In short, mangrove litter-fall is many times higher than the above-ground organic matter produced by other terrestrial ecosystems.

High litter production is perhaps the most important service of mangroves in the coastal areas of Mexico's arid northwest. This litter represents a major source of organic material and nutrients that flow into adjacent communities and nurtures coastal food chains, contributing with energy sources for bacteria and filter-feeders. Eventually, a part of this litter will accumulate in the mangrove soil, buried by *Uca* fiddler crabs, or will sink into the lagoon bottom accumulating there in the form of organic sediment and in so doing contributing to the mitigation of anthropogenic CO_2 in the atmosphere.

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CORAL REEFS

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and Luis E. Calderón-Aguilera[3]

In spite of their small size in NW Mexico, coral reefs harbors one of the highest numbers of species per area unit. The geological history of corals shows that coral community composition six million years ago (Late Miocene) was entirely distinct than the present fauna, with three abrupt shifts coupled with two periods of relative stasis in species composition; shifts occurred during 6 to 5 My, 3 to 2 My, and 1 My to actual times. Considering the multiple and severe modifications that are in course in the oceans as a consequence of global change, we suggest different scenarios regarding future frequency of coral bleaching in the southern Gulf of California, changes in species distribution, and the effects of the increasing ocean acidity by increasing carbon dioxide concentration in the atmosphere. The three independent analyses performed suggest that the status of coral communities and reefs of the Gulf of California is not optimum, and might deteriorate in the future. Higher temperature and acidification will affect coral survival and physical integrity of reefs, even if other agents such as bioerosion, predation and diseases are excluded from the picture. The models of coral potential geographic distribution evidences that the eastern coast of the Gulf may become a more hospitable place for corals than today, unfortunately models also predict that the rate of temperature increase in the area is highest, and thus the possibility of bleaching intensifies.

1. INTRODUCTION

Coral reefs are remarkably biodiverse ecosystems, which harbor hundreds of species. There are two main reasons to explain this circumstance: an elevated local productivity and structural heterogeneity. The productivity is caused by the carbon-fixing activity of the phytoplankton, cyanophytes and other algae, but mostly because of the symbiotic relationship between the coral (an animal) and microscopic dinoflagellate cells called zooxanthellae. The coral provides housing to the algae and in turn the latter supply its host with food and an adequate chemical environment for calcium carbonate deposition. There is a surplus in the amount of energy supplied by the algae to the coral, and these compounds (carbohydrates and lipids) are expulsed as mucus, which turns to particulate carbon or it is directly consumed by a myriad of other organisms resident in the coral heads (crabs, gastropods), which then are eaten by fishes or larger invertebrates, and finally ends as food for higher carnivores such as sharks, barracudas and even marine mammals. In short, the symbiotic relationship between corals and zooxanthellae are the base of the intricate food webs characteristic of reefs worldwide.

On the other hand, coral reefs are biogenic structures that modify the substrate where they grow upon. Species that build reefs are called hermatypic, a word that means "reef-builders", and are restricted to shallow waters because the zooxanthellae need abundant light for photosynthesis. However, there are others corals that do not have algae, named azooxanthellate that live deep in the ocean and may form conspicuous structures on the sea floor, and at depths of 300 m or more.

In northwestern Mexico there is only one coral reef in Cabo Pulmo (23ºN), close to the tip of the Baja California Peninsula (see Figure 1). The framework is small but nevertheless the amount of energy supports the highest fish biomass in any reef of the Gulf of California (Aburto-Oropeza *et al.* 2011). In addition, reef corals occur at five states in NW Mexico (Baja California, Baja California Sur, Sonora, Sinaloa and Nayarit) and the entire region harbor 24 species of zooxanthellate and 30 species of azooxanthellate corals. This means that 77% and 85%, respectively, of all coral species reported for the Mexican Pacific (Reyes-Bonilla *et al.* 2005) are represented in this region. The ratio of zooxanthellate: azooxanthellate is quite different among states; *e.g.* Baja California only have two zooxanthellate species and 22 azooxanthellate, while Nayarit have 20 zooxanthellate and 5 azooxanthellate (see Figure 1). However, this may be explained by the sampling effort conducted in each region, because the deep water corals require a research vessel and the Gulf of California has been the target of numerous cruises, but notwithstanding the Gulf of California is one of the richest areas for coral occurrence in Mexico.

The first reports of coral species in the region come from expeditions conducted in the XIX century by institutions from the United States (Reyes-Bonilla 2003), but in the last two decades of the XX century and the beginning of this century, most studies have been carried out by Mexican researchers.

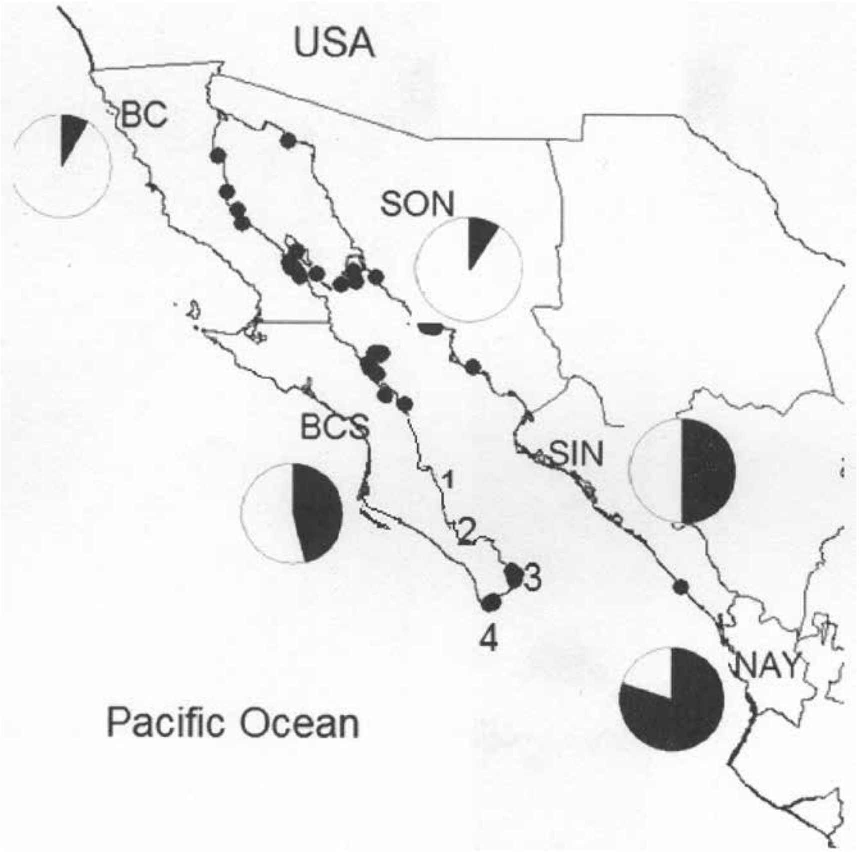

FIGURE 1. Locations of the main coral communities in the Gulf of California. Pie charts inside each state represents proportion of zooxanthelate (filled) and azooxanthelate (blank) corals.

2. CORALS OF THE PAST

Studies of stony corals in the Gulf of California have mainly focused on living species and few of these works have analyzed fossil taxa. In addition, this kind of research has been sporadic, incidental and to some extends rudimentary, and generally devoted to species description, faunal listings and reviews of the geographic affinities of the fauna (López-Pérez 2005). Recently, however, new attention has been drawn to new records of coral species (López-Pérez 2008), to the lithology, age and paleoenvironment of buildups (Johnson and Ledesma-Vázquez 1999, Mayer and Vincent 1999, Halfar *et al.* 2001, DeDiego-Forbis *et al.* 2004, Johnson *et al.*

2007), and to issues regarding scleractinian diversification in the Gulf of California (López-Pérez and Budd 2009). On this ground, here we summarize published information on fossil corals and perform a quantitative analysis of the change in species composition in the Gulf in order to highlight the relevance of the area in the development of the eastern Pacific coral fauna.

We analyzed presence/absence data collected during field expeditions to the Baja California Peninsula in June-August 2002, January 2003, June-July 2003, and January 2005. Data were arranged in time bins of one million years of duration during the last 6 million years. In addition, a relative abundance matrix was created by counting the number of specimens per species collected within each assemblage, and assigning codes for rare, common, abundant, and supper-abundant, such that: 1 specimen = rare, 2-3 specimens = common, 3-9 specimens = abundant, and > 9 specimens = super abundant. Both, presence/absences and relative abundances of coral taxa among assemblages were compared using the Bray-Curtis dissimilarity index, and processed with a non-metric Multi-Dimensional Scaling (MDS). Following MDS, the relative abundance matrix was evaluated through similarity analysis (ANOSIM) to detect changes in species composition and abundance through time (Clark and Warwick 2001).

Ordination (MDS) on presence/absence data (see Figure 2) show that, for the stony coral fauna in the Gulf of California during the last six millions years, there were clear differences in community structure between time bin intervals. Several elements are worth to mention. First, coral community composition six million years ago (Late Miocene) was entirely distinct than the actual fauna, indeed, they are located at opposite ends of the graph. Second, note that there have been three abrupt shifts coupled with two periods of relative stasis in species composition; shifts occurred during 6 to 5 My, 3 to 2 My, and 1 My to actual times, particularly, species composition shifted abruptly during the last million, whereas stasis occurred between 5 to 3 My and 2 to 1 My. Finally, low similarity levels persisted from Late Miocene to Early-middle Pleistocene due to the presence of *P. panamensis* and *Pocillopora capitata* in fossil buildups during the last 5 My whereas the abrupt shifts was favored by the constant addition and extinction pulses of Caribbean derived taxa that originated in Gulf of California coral reef communities (López-Pérez and Budd 2009). It is worth to mention that except for the living *P. panamensis* and *P. capitata*, no other taxa or its descendants are known in Gulf of California or eastern Pacific reefs (Reyes-Bonilla *et al.* 2005), although related fauna (*Siderastrea, Favia, Diploria, Dichocoenia, Solenastrea, Eusmilia*) still persist in the Caribbean (Budd *et al.* 1994).

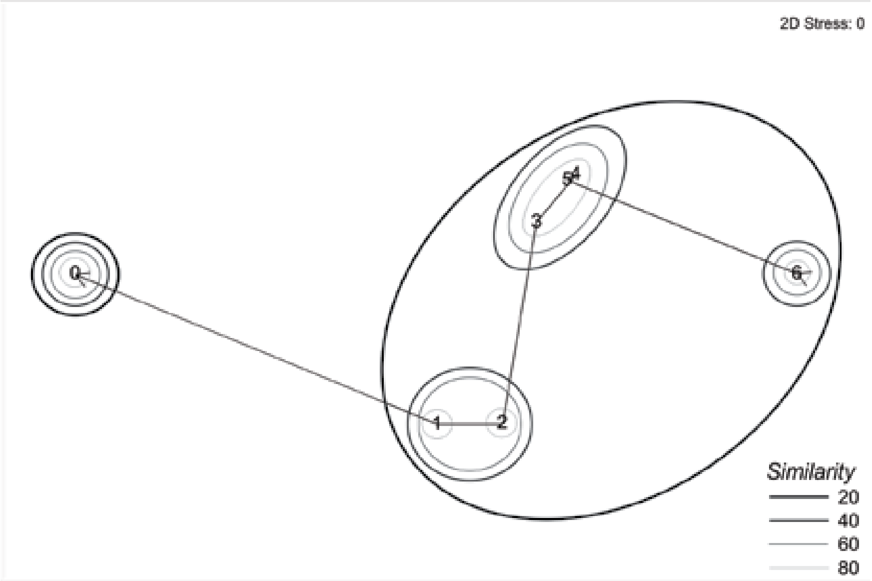

FIGURE 2. Qualitative change of coral reef communities during the last six million years in the Gulf of California, Mexico. Dissimilarities among time bin intervals (one million years of duration; 6 = Oldest, 0 = Recent) were generated with a Bray-Curtis index from a presence/absence matrix. Distance map produced by multidimensional scaling. Similarity contours = 20, 40, 60, 80 %; overlay trajectory = arrows.

Two elements converge in the abrupt shift that favored the current composition of Gulf and eastern Pacific coral fauna: the extinction pulses that drove the local extirpation of Caribbean related fauna between 3-1 My (López-Pérez and Budd 2009), and the immigration of species into the Gulf from the Indo-Pacific (Dana 1975). As demonstrated by López-Pérez and Budd (2009), both pre-turnover (Caribbean related) and post-turnover (Indo-Pacific) taxa does not coincide in space or time, therefore ruling out the role of biological interactions or ecological replacement as the leading role on species extinction; on the contrary, Indo-Pacific species invade the Gulf at a steady but sporadic rate after the arrival of *Pavona clavus* during lower to Middle Pleistocene near the mouth of the Gulf (López-Pérez 2008).

Two further figures depict species relative abundance changes in Gulf coral communities from Middle Pleistocene to the Recent (see Figure 3). *Porites panamensis* flourished and constructed relatively large and monospecific reefs from Punta Chivato to Isla Cerralvo in Pleistocene times (Johnson *et al.* 2007) and became the most widespread species in living eastern Pacific coral communities and reefs

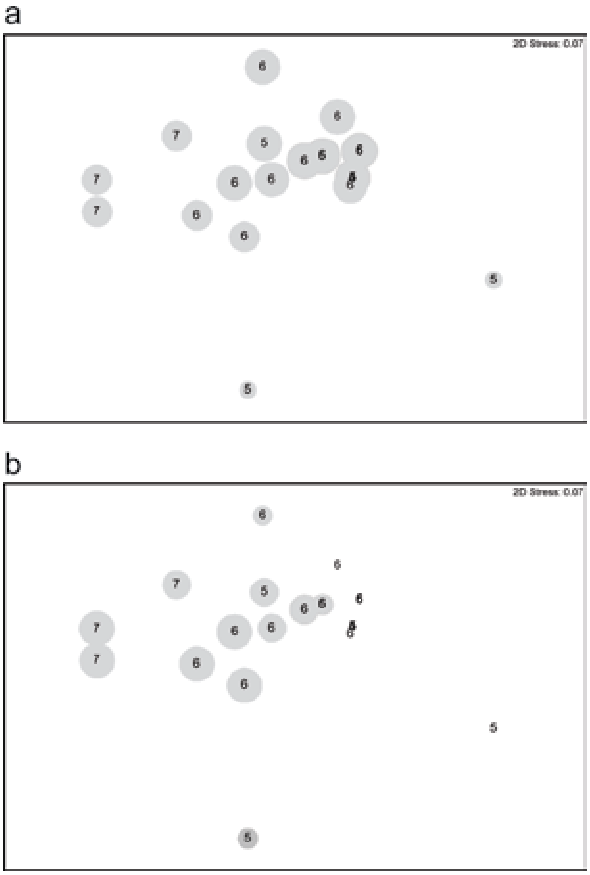

FIGURE 3. Quantitative change of coral reef communities from Middle Pleistocene to Recent in the Gulf of California, Mexico. Dissimilarities among assemblages were generated with a Bray-Curtis index from an abundance matrix. Distance map produced by multidimensional scaling. 5 = Middle Pleistocene; 6 = Late Pleistocene; 7 = Recent. Bubbles = species relative abundance. (a) Overlay *Porites panamensis* relative abundance. (b) Overlay *Pocillopora capitata* relative abundance.

(Reyes-Bonilla *et al.* 2005). Figures 3a/3b illustrate the shift from *P. panamensis* to *Pocillopora* spp. dominated communities in the Gulf; in particular, it is remarkable how *P. capitata* has increased its abundance from Middle Pleistocene to the Recent (see Figure 3b), while *P. panamensis* has remained stable during the same time interval (see Figure 3a) becoming a relatively minor element in the living south and central coral communities as demonstrated by Reyes-Bonilla and López-Pérez (2009). On this ground, it can be safety claimed that rather than be caused by the lower contribution of *P. panamensis* to living reefs, community change was due to the increase of *P. capitata*; therefore the relative abundance of *Porites* and *Pocillopora* in the Gulf, can be explained by a dilution effect instead of the competitive displacement of *P. panamensis* by *P. capitata* from Gulf communities.

So far, we have reviewed the past and current situation of the coral communities and reefs of the Gulf, and the last section will address its potential future. It is understandable that due to the multiple and severe modifications that are in course in the oceans as a consequence of global change, it is of the foremost importance to make use of updated information to suggest feasible scenarios about how coral communities will behave, and from there to examine if their distribution, abundance and status might be modified by the new set of conditions. In the following pages we deal with three topics related to the rising sea surface temperatures: future frequency of coral bleaching in the southern Gulf of California, changes in species distribution, and the effects of the increasing ocean acidity by increasing carbon dioxide concentration in the atmosphere.

3. CORAL BLEACHING

This phenomenon represents the loss of the relationship between the zooxanthellae (symbiont dinoflagellates) and their coral hosts, and has become one of the main worries for the health of coral reefs worldwide as its consequences are plenty, impact the entire ecosystem, and is practically impossible to control as it can affect entire oceans (Baker *et al.* 2008). Bleaching tends to occur when conditions are atypical, including several cumulative weeks with high ocean temperature, high irradiance and low wind stress (Hoegh-Guldberg *et al.* 2007). However, many studies have indicated that the current rate of sea temperature increase will lead to a situation when the loss of algae will happen much more frequently and eventually become chronic (yearly), as the temperature surpass a given limit. This marker is known as the "temperature threshold" (Goreau and Hayes 1994, Podestá and Glynn 1997), and represents an increase of 1°C above the long term average temperature of the warmest month (*e.g.*, if August is the warmest month in a given site and its average is 28.5°C, then the local bleaching threshold is 29.5°C). In this section we will present the bleaching thresholds of the main reef areas of the Gulf, located on the southeastern tip of the Baja California Peninsula, and use a simple and conservative statistical model to assess when coral bleaching will become chronic and occur at least one month every year.

To determine the current bleaching threshold, quadrats of 1° x 1° latitude and longitude were selected to encompass four key areas for coral development in the Gulf: Los Cabos region (south and east limits at 22°N, 109°W), Cabo Pulmo (23°N,

TABLE 1. Bleaching threshold, annual rate of increase and year when bleaching will become chronic at selected sites in the Gulf of California.

Site and latitude	Bleaching threshold (°C; calculated from 1984-2008)	Slope (annual rate of increase)	Year when bleaching will become chronic
Los Cabos (22.5°N)	29.81	0.0114 + 0.0032	After 2050
Cabo Pulmo (23.5°N)	30.27	0.0089 + 0.0031	After 2050
La Paz (24.5°N)	30.03	0.0005 + 0.0033	2046
Loreto (25.5°N)	29.78	0.0178 + 0.0033	2034

109°W), La Paz (24°N, 110°W) and Loreto (25°N, 111°W). At each quadrat we analyzed monthly data of sea surface temperature from the Reynolds SST analysis (www.nhc.noaa.gov/aboutsst.shtml) considering the time span of 1984 to 2007 (N=288), as suggested by Sheppard (2003) and Eakin *et al.* (2008); further, we calculated the bleaching threshold on the basis of the average temperature of August, which in all cases was the warmest month. The next step was to perform individual linear regressions for each quadrat, using the year as independent variable and the temperature of each month as dependent; this way we obtained the monthly rate of increase directly from the slope of the twelve lines. Finally, we extrapolated the regression lines to calculate the expected temperature for each month from 2008 to 2050, and performed a general analysis of year versus average temperature (N=24) to estimate the general trend of temperature change at each quadrat. The linear approach was considered conservative since most global change models advise that the trend of ocean warming is faster than monotonic (Donner *et al.* 2009), and thus our predictions can be placed on the safe side.

Our results indicate that the slope of temperature increase in the 25 years analyzed differs noticeably among sites, as in Loreto and Los Cabos is two to three times higher than in La Paz and Cabo Pulmo (see Table 1). This is a clear indication that warming is not homogeneous in the study region nor has a latitudinal array, but instead is driven by local conditions; for example, in the case of La Paz the rate is slower probably as a consequence of the spring wind-induced upwelling that occur west of San José Island. The bleaching threshold is not constant either, being highest at Cabo Pulmo and lowest at Loreto, with a difference of almost 0.5°C between these areas (see Table 1). These finding points out that at Cabo Pulmo corals are possibly more tolerant to sea water temperature increases, and that may be one of the reasons why they survived the last two intense bleachings in 1997 and 2008, and minor events in 1987, 2007 and 2009 (Reyes-Bonilla 2003, LaJeunesse *et al.* 2007, Reyes-Bonilla and López-Pérez 2009, Reyes-Bonilla unpublished data).

Considering the rate of increase and the bleaching threshold from the linear regression, we predict that the two southernmost reef areas of the Gulf of California may not experience chronic bleaching in the following four decades, while by 2034 the problem may develop yearly (during August and September) at Loreto and after 2046 in La Paz (see Table 1). By 2050, Loreto corals may experience loss of zooxanthellae from July to September, while at La Paz the bleaching will be present only in September, because by that time we predict that this will be the warmest month of the year, instead of August.

Our model and the actual temperature trends (see Figure 4) support the idea that the central part of the Gulf will be in more thermal stress than the south, probably as the latter is more influenced by the California Current during winter and early spring (Kessler 2006). However, as the current temperature in these areas is not adequate for reef corals, we might suggest that global warming can bring conditions that will actually improve the situation, at least temporarily, for reef corals in the eastern Gulf of California. We fear that with so high warming rate, the threshold of adequate conditions may be surpassed and corals might experience chronic bleaching soon, a condition that will avoid reef development in that region of the Gulf. All these observations are important as several authors (Glynn 2001, Reyes-Bonilla *et al.* 2002, Precht and Aronson 2004) have suggested that the relatively colder waters of the Gulf would provide shelter to corals during global warming; unfortunately, that may not be the case in the entire region.

4. CORAL POTENTIAL DISTRIBUTION

The second analysis consisted in the application of niche models to determine possible changes in coral species distribution and consequently richness, along the Gulf. This subject is important as the continuous increase in sea temperature occurred in the last 25 years, has favored the colonization of the Gulf by several coral species such as *Leptoseris papyracea* (first found in 1997; Leyte-Morales *et al.* 2001) *Psammocora superficialis* (found in 1997; Reyes-Bonilla 2003) and *Pavona varians* (found in 2003; Reyes-Bonilla *et al.* 2005) and, at the same time, it has affected the health of an endemic coral, *Porites sverdrupi*, which has reduced its northern distribution range about 250 km, currently from Los Cabos (22ºN) to San José Island (25ºN; Reyes-Bonilla and López-Pérez 2009). The most recent distribution shifts was observed in 2009; the previous *Pocillopora verrucosa* northern geographic limit was Loreto

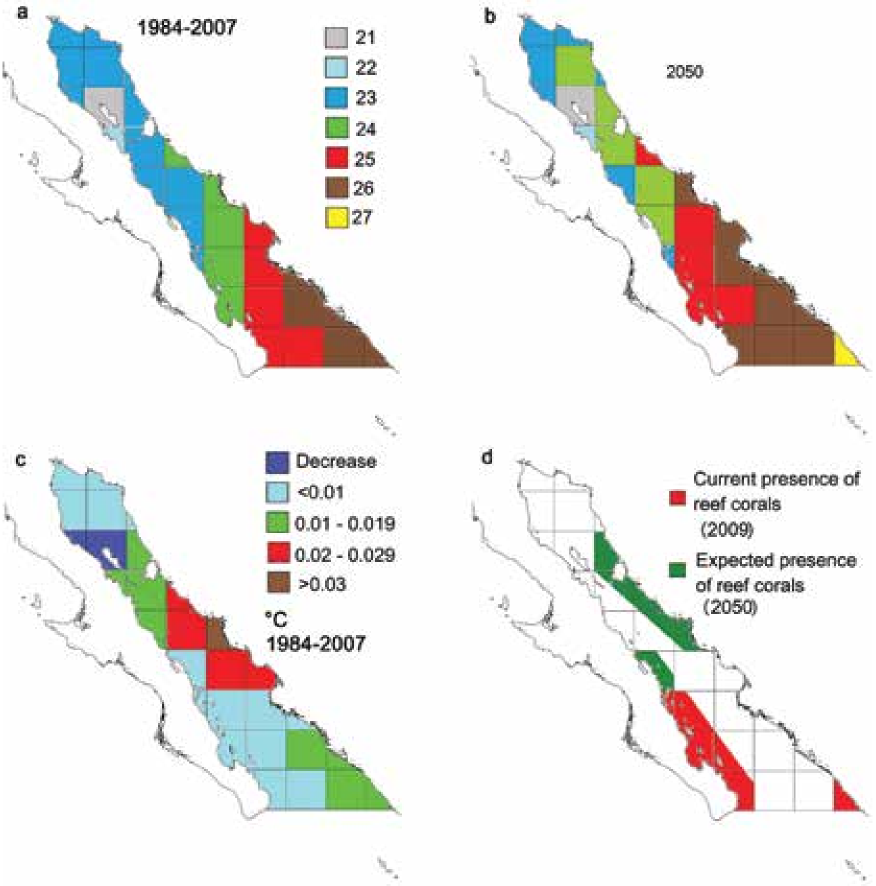

FIGURE 4. (a) Average sea surface temperature of the Gulf of California (1984-2007); (b) Expected temperature by 2050; (c) Rate of temperature increase (linear model; yr -1) from 1984-2007; (d) General result of the MAXENT model for reef corals of the Gulf.

(25°N), but currently it is found at Concepción Bay (26.5°N), while P. *damicornis* has moved about 100 km north, from Agua Verde Bay to northern Loreto Bay.

To model the potential distribution range for the each of the 19 hermatypic coral species that inhabit the Gulf, we used over 1,500 georeferenced records from the area published by Reyes-Bonilla *et al.* (2005). The information was processed using MAXENT (maximum entropy modelling; Tittensor *et al.* 2009) along with 22 environmental variables obtained for all 29 squares of 1° x 1° lat-long area that cover the Gulf down to the parallel 22°N. The environmental variables considered were the surface maximum, minimum and average values of chlorophylla (SEAWIFS and MODIS-AQUA satellites, monthly data from 1997-2008; http://las.pfeg.noaa.gov/oceanWatch/oceanwatch.php#, and http://reason.gsfc.nasa.gov/OPS/Giovanni/ocean.aqua.shtml), salinity and nutrient concentration (nitrate, phosphate and silicate; monthly data from the World Ocean Atlas 2005, average 1955-2004; www.nodc.noaa.gov/OC5/SELECT/woaselect/woaselect.html), and alkalinity (calculated from salinity and temperature following the algorithm of Lee *et al.* 2006), plus a dummy variable indicating the type of substrate (hard or soft; from the general classification presented by Moreno-Casasola *et al.* 1998). Further, we substitute the historical temperature data with that predicted with our linear models for 2030 and 2050 for each 1° x 1°quadrat, and re-run the models. Finally, we determine that a given area is acceptable for reef coral occurrence if the expected number of species is higher than 6, the current number at Loreto (Reyes-Bonilla 2003).

Results indicated that most of the western Gulf of California has fair oceanographic conditions for coral development as nutrient concentration is not so high and rocky bottoms are dominant in that region. However, the limiting factor is temperature, as most species prefer relatively warm waters because they have colonized the eastern Pacific from the west (Reyes-Bonilla 2003); in fact, the key factor is lowest yearly temperature, as most species are not able to survive if winter temperature is lower than 18°C. The maps of potential distribution (not shown) point out that from 2007 to 2030 there will be few range shifts, as only two species will move from 23°N to 24°N, on the coast of the Baja California Peninsula (*Pavona varians* and P. *duerdeni*), but by 2050 seven out of 19 species (37% of the total) will move northward; that said, today species turnover rate is slow but four decades from now rise to over 30% at latitudes 27°N and 30°N. It is important to notice that the analysis identified that the increase in richness at 27°N will be caused by colonization of the eastern coast of the Gulf by *Pavona gigantea* and *Pocillopora verrucosa*. Finally, the only species that reduces its distribution range was *Porites sverdrupi*, which according to his potential distribution map will be restricted to waters north of 26°N in the Gulf.

Figure 4d highlight the areas for development of reef corals by 2050. As observed, the rise in temperature will remarkably increase the potential habitat for reef corals by 2050, and is expected than northern Sinaloa and southern Sonora (27° to 29°N) may soon have elements of this ecosystem. The addition of these species may represent a boost in species richness in those areas as corals provide new resources and also facilitate the entrance of western Pacific species (crabs, fishes, gastropods) that are not present in the eastern Gulf of California nowadays.

5. OCEAN ACIDIFICATION

Ocean acidification has been called "the other CO_2 problem" because at the same time that carbon dioxide increases atmospheric temperature, it also acidifies the ocean water as a consequence of hydrogen ions liberated by the carbonate system (Doney *et al.* 2009). The situation was first noticed in the 1990s (Kleypas *et al.* 1999) and has caused serious concern as acidification is not only damaging shallow water reefs but also can affect deep water scleractinian species (Guinotte *et al.* 2006, Hoegh-Guldberg *et al.* 2007). It is predicted that lower pH values will reduce calcification rate for both the marine benthos and plankton, and can be especially damaging for larvae and juveniles (Fabry *et al.* 2008, Munday *et al.* 2008). In the specific case of reefs, the problems are plentiful, including depleted recruitment of corals and other invertebrates, lower tolerance to predators, and especially a more fragile reef framework (Baker *et al.* 2008).

To analyze the current and future status of omega aragonite in the southwestern Gulf of California, we followed the method described by Manzello *et al.* (2008) on the same 1° x 1° lat-long quadrats. We used average monthly salinity, phosphate and silicate concentration at depths from surface to -50 m (data from the World Ocean Atlas 2005, average 1955-2004; www.nodc.noaa.gov/OC5/SELECT/woaselect/woaselect.html); monthly temperature for 2008 from a combination of the WOA atlas and the MODIS-AQUA satellite data; monthly atmospheric carbon dioxide concentration from air flask samples taken at La Paz in 2008 (Scripps Institution of Oceanography CO2 program; http://scrippsco2.ucsd.edu/data/flask_co2_and_isotopic/monthly_co2/monthly_bcs.csv); calculated alkalinity following Lee *et al.* (2006) algorithm, and included all cited parameters in the program CO2SYS. In addition, to forecast the possible carbonate saturation state from 2010 to 2050, we calculated yearly average of nutrients and salinity and considered them as constant as there is no useful method to estimate future values (Donner *et al.* 2009). Then we used the expected value of sea surface temperature from linear extrapolations described earlier, calculated alkalinity with Lee *et al.* (2006) procedure, and calculated the anticipated carbon dioxide concentration according to the power model of the Mauna Loa Observatory (http://scrippsco2.ucsd.edu/data/in_situ_co2/monthly_mlo.csv) in order to calculate the possible omega aragonite value with CO2SYS. Finally, to evaluate the status of Gulf coral communities and reefs we took as landmark the figure of 3.28 + 0.09, considered by Kleypas *et al.* (1999) as the lowest limit for coral reef formation.

As shown in Figure 5, aragonite conditions were very different among reefs, even when they are geographically nearby (between Loreto and Los Cabos the distance

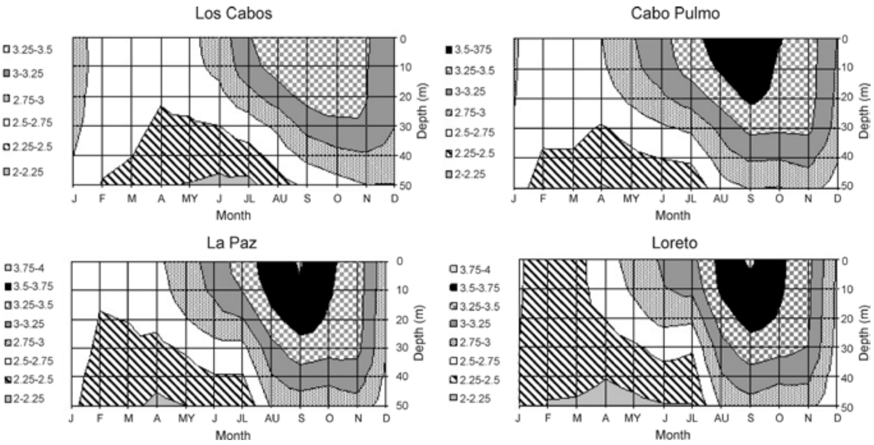

FIGURE 5 Bathymetric distribution of omega aragonite in four rocky and coral reefs of the Gulf of California.

is less than 300 km). The southernmost region, Los Cabos, bordering the Pacific Ocean, is characterized by low omega values (range of 2.18 to 3.49), and the best seasons for coral calcification is summer and fall (from late July to November), when Ω surpasses 3.25. Analyzing the depth levels it can be seen that below 30 m the conditions do not allow for a healthy development of coral reefs, and at -20 m only September and October are adequate. On the other hand, from Cabo Pulmo to Loreto the conditions are much better, but still far away from the ideal condition. From mid June to mid November the calcification index was over 3.25, and peaks in September when it reached 3.66 in Cabo Pulmo and over 3.77 in La Paz and Loreto. This value is similar to the lowest monthly average in the Caribbean Ocean during 2009 (http://coralreefwatch.noaa.gov/satellite/oa/saturationState_GCR.html). Finally, the possibility to construct reefs exists in waters deeper than -30 m, and very good in summer months down to 20 m depth.

There are two references addressing the omega aragonite value in the southern Gulf of California. Kleypas *et al.* (1999) calculated that surface value in the mid 1990s was from 3.34 to 3.49, much higher than that calculated for 2008 (see Figure 3), from 3.00 + 0.14 in Loreto, to 3.12 + 0.11 in Cabo Pulmo, while Manzello *et al.* (2008) show that the Gulf has a mean omega of around 2.9, a little lower than the calculated here. Dismissing the small differences in estimated values, the key point here is that the main coral communities and reefs of the Gulf are currently under the threshold for reef formation, as it occurs in other areas like the Galápagos Islands, subtropical

Japan and southern Australia, which periodically are under the influence of upwelling (Kleypas *et al.* 1999). It is expected that moving northward in the Gulf, where acidity and primary productivity are higher by effect of the colder water (more catch of atmospheric CO_2) and continuous tide and wind disruption of the thermocline (Álvarez-Borrego 2007), the situation is even worse.

If conditions nowadays are difficult for reef corals in the Gulf, the future seems bleaker. Most studies show that ocean acidity will be higher in the future as a consequence of increasing carbon dioxide concentrations (Hoegh-Guldberg *et al.* 2007); concurrently, we showed that coral calcification in the Gulf will become rougher during the following decades. As indicated by Manzello *et al.* (2008) for the Galápagos Islands, Panamá and Costa Rica, more acid ocean water represents brittle coral skeletons and a heightened effect of chemical and biological erosion. If this is the case, even with no increase in frequency and strength of tropical hurricanes and cyclones, the physical stability of reef areas in the Gulf will be compromised, and thus their function and ecosystem services will be severely affected, with unknown but deleterious consequences for the human communities in northwestern México.

6. FINAL REMARKS

The three independent analyses performed point out toward a conclusion: the status of coral communities and reefs of the Gulf of California is not optimum, and might deteriorate in the future. Higher temperature and acidification will affect coral survival and physical integrity of reefs, even if other agents such as bioerosion, predation and diseases are excluded from the picture. The models of coral potential geographic distribution evidences that the eastern coast of the Gulf may become a more hospitable place for corals than today, unfortunately models also predict that the rate of temperature increase in the area is highest, and thus the possibility of bleaching intensifies. Reef corals are very long-living animals with extended generation times, and for that reason local adaptation is usually quite slow (Sheppard *et al.* 2009); nevertheless, dramatic mortality events may accelerate it (Donner *et al.* 2005) or in the specific case of bleaching, the exchange of clade types is a potential option to do so (Baker *et al.* 2008). We expect that the low effective population size of coral populations north of 25°N may boost the speed of evolutionary change for the current fauna, and that Indo Pacific colonizing species will also do well under future conditions. That way, reef coral environments will survive throughout the century; however, if this is not the case, we may be on the verge of the loss of a rare but nevertheless important marine ecosystem in the Gulf of California.

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THE BAJA CALIFORNIA PENINSULA WEST COAST: A TRANSITIONAL ZONE BETWEEN BREEDING AND FEEDING GROUNDS FOR MIGRATING WHALES AND SEASONAL FEEDING HABITAT FOR OTHER CETACEANS

Diane Gendron[1] and Milena Mercuri[2]

The coastal area of the Baja California west coast is known as an important area for all migrating whales since the early whaling period. This area represents a migrating corridor and also serves as breeding and feeding area for several species of cetaceans. While the coastal habitat is relatively non developed and still provides a good quality habitat for cetaceans, it should be protected from gillnet fishing at least seasonally. A seasonal rhythm of cetacean stranding was associated with natural processes occurring within the ecosystem with higher incidences in the late spring and early summer months, coinciding with the seasonality of the highest rates of net primary production in the area. Regulation of whale-watching should be promoted particularly in non-protected coastal areas along the Baja California Peninsula.

Keywords: Baja California west coast, cetaceans, whaling, distribution, cetacean stranding, anthropological impact.

1. INTRODUCTION

South of the vastly developed coast of California, lays the Baja California Peninsula (see Figure 1). With few human settlements, this dry and desert land, long considered a Mexican territory, was untouched until recently, when coastal developments and marine traffic have increased very fast, principally at both extremities. Along more than 2,000 km of coastline, there are very few shelters to anchor for protection and no marinas to purchase supplies, so most of vessels sail in transit between California or Ensenada to Cabo San Lucas.

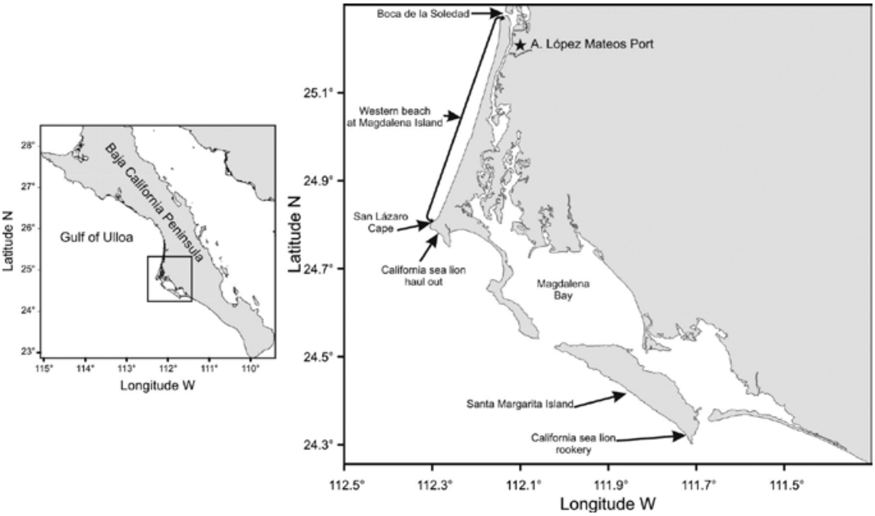

FIGURE 1. The Baja California Peninsula showing the study site at Magdalena Island.

The ocean along this coast is where the southern limit of the California Current joint with the northern limit of the North Equatorial Current and is characterized by the high biological productivity generated by seasonal upwellings and frontal systems (Lluch-Belda *et al.* 2003). The pelagic area off the southern portion is recognized as one of the Northeastern pelagic hotspot for conservation of marine species (Etnoyer *et al.* 2004). The area has never been intensively studied. Since 1997 CICESE initiated the Mexican program IMECOCAL (Programa de Investigaciones Mexicanas en la Corriente de California http://imecocal.cicese.mx/) to monitor the area north of Bahía Magdalena following the CALCOFI (California Cooperative Fisheries Investigations, www.calcofi.org) oceanographic cruises made in the past. Unfortunately due to the high cost to sustain these oceanographic cruises, in addition to the intense research activities onboard on a relatively small ship, cetacean assessments has not been part of these surveys.

Along this coast, several cetacean species are using the area partially or throughout the year, but the knowledge of their habitats, movements and feeding habits along the coastal and pelagic areas remain poorly known. It is therefore the objective of this chapter to gather the past and present information to highlight the significance of this area as an important migratory corridor for several whales and also as a seasonal feeding area for other cetaceans. A special section will illustrate the use of cetacean stranding surveys in a portion of the coastal area of the Peninsula to gather knowledge on the temporal use of the habitat by these populations.

The first piece of information on cetaceans along this coast was revealed by the detailed mapping of the whales caught around the world from 1761 to 1920 by Townsend (1935). These included the slow moving whales, such as the sperm whales, the humpback whales, and the North Pacific right whales. Another source of information on several cetacean descriptions and distributions along this coast comes from Scammon's book (1874 reprinted in 1968), the famous captain of a whaling ship that discovered the gray whales breeding lagoons. Information on other whales, is available from the period between 1924 and 1929 when the Norwegians whalers revealed the seasonal presence of faster rorquals such as blue, Bryde's and sei whales based on their reports of each species captured in the area (Tønnessen and Johnsen 1982). While several species were being protected in the 60's, scientific cruises were made to assess these reduced populations due to whaling (Rice 1966, 1974). Thereafter, more cruises conducted by different institutions: the Universidad Autonoma de Mexico (Urbán and Aguayo 1985), the Southwest Fisheries Science Center (Mangels and Gerrodette 1994), and CICIMAR (Gendron 2002, unpublished data), will help to describe the seasonal distribution of large whales in this particular area.

2. GRAY WHALE (*ESCHRICHTIUS ROBUSTUS*)

One of the most important aspects that favored the fast recovering of the gray whales is perhaps due to the relatively intact coastal area of the Peninsula including their well known breeding lagoons: Laguna Ojo de Liebre (Scammon's lagoon), Laguna San Ignacio and Bahía Magdalena (Scammon 1968). These have remained essentially unchanged since the end of the whaling of this species during the 30's. Except Bahía Magdalena, the other lagoons are protected areas that are included in the El Vizcaíno Biosphere Reserve, which is also listed internationally as a UNESCO World Heritage Site and a Ramsar protected wetland (Hoyt 2005).

The most important change that occurred since these whales were protected, was the start of the salt exploiting by the Compañía Exportadora de Sal, S.A. in Guerrero Negro in the 50's and the start of the whale-watching activities mostly in San Ignacio lagoon in the 70's and expanding south to Bahía Magdalena (Gardner and Chávez-Rosales 2000) and to Los Cabos, and north to Scammon's lagoon and off Ensenada.

An excellent review and summary on gray whales whaling history, conservation and research in Mexico is documented by Urbán *et al.* (2003). Their coastal migration is well known from the Bering Sea passing different coastal points at precise dates along the north American coast reaching the Baja California breeding lagoons mostly in January (Rice and Wolman 1971, Rugh *et al.* 2001). Pregnant females arrive first and use the most intern and protected areas to give birth to their young and to nurse them (Rice and Wolman 1971), and will spend in general more time in the lagoons than the males or non pregnant females (Jones and Swartz 1984, Gómez-Gallardo Unzueta 2004). These single whales gathered at the entrances to reproduce, stay for shorter periods in the lagoons and may move from one breeding lagoon to another (Jones and Swartz 1984). South of the Bahía Magdalena they are scattered along the coast down to Los Cabos, and during El Niño years they extend their range south and are found well inside the Gulf of California (Urbán *et al.* 2003). Although gray whales mainly feed in the northern areas (Kim and Oliver 1989) they have been observed with sand coming out of their mouth while surfacing near the entrance of the lagoons (S. Lanham, pers. com.) and also observed chasing sardines at surface in Magdalena Bay (Gendron, not published).

Single whales are the first to initiate the northbound migration while the females accompanied by their calf are the last to leave the lagoons with a difference of one month observed for whales in San Ignacio lagoon (Jones and Swartz 1984). A single gray whale radio tagged revealed a clear coastal northern route at a mean distance of 7.3 km in water less than 100m deep, except when crossing the Vizcaíno Bay (Mate and Urbán 2003).

3. HUMPBACK WHALE (*MEGAPTERA NOVAEANGLIAE*)

Another species that principally uses the Baja California west coast seasonally is the humpback whale. This species is also well known to aggregate in breeding areas, but prefers islands or specific areas along the coast instead of lagoons. The Mexican humpback breeding areas include the southern coasts of Baja California Peninsula, mainland coast of central Mexico and the Revillagigedo Islands (Rice 1974). A fourth area where humpback whales are sighted mostly in winter is the Gulf of California (Urbán and Aguayo 1987, Urbán *et al.* 2000). As for the west coast of the Baja Peninsula, Townsend (1935) indicated aggregation of humpback whales captured in this area and along the central Mexican coast. It is interesting to note that Scammon (1968) mentioned the area off Bahía Magdalena as one of the three best areas to capture them, and coincide with the reported of 1,568 humpback whales caught there between 1924 and 1929 by the Norwegian whalers (Tønnessen and Johnsen 1982). The aggregations of humpback whales along the coast may indicate they feed during their movement north, but aside feeding behavior described in the Gulf of California (Gendron and Urbán 1993), no other feeding observation have been reported.

There are two migration routes for the humpback whales wintering in Mexico, the whales wintering in the coastal mainland and Baja California region migrate along the coast to reach California-Oregon-Washington and British Columbia, while the ones wintering around the Revillagigedo islands are separate from the American stock and probably migrate to the Aleutian islands and or the Bering Sea (Urbán *et al.* 2000, Calambokidis *et al.* 2001).

4. BLUE WHALE (*BALAENOPTERA MUSCULUS*)

During the mid 19th century, Scammon (1968) described aggregations of blue whales along the coast of Baja California, close to Cedros Island "it was the month of July and the sea, as far as the eye could discern, was marked with their huge forms and towering spouts". Despite their velocity, some were captured in the inshore areas by Tortuga bay, Asuncion Island, and San Quintin (Scammon 1968). At the start of modern whaling (1913–1914), the Norwegians caught eighty-three blue whales off Bahía Magdalena (Tønnessen and Johnsen 1982). They returned a decade later with two floating factories and captured about 870 blue whales between the months of March and June during the 1924–1929 period (Tønnessen and Johnsen 1982), which represent almost half of the blue whales caught along the shore of the North American west coast. A last expedition was made, in conjunction with Mexico under the company named Esperanza in 1935, but no blue whales were observed.

About 40 years later, the Baja West coast area was declared by Rice (1966, 1974) as one of the world's last remaining blue whale sizable stocks. From these cruises, he reported the same general distribution, with large aggregations of blue whales from February to July relatively close to shore. Between 1994 and 1996 two coastal cruises and several aerial surveys made along the whole west coast of Baja California showed blue whales in February and March off the southern portion of the west coast and by June, they were distributed along the entire coastal area of western Baja California (Gendron 2002). In addition, blue whales apparently follow the shift in seasonal productivity around the Peninsula, from the Gulf of California during winter and early spring to the west coast between April and July (Santamaría-Del Ángel and Álvarez-Borrego 1994) where and when surface feeding is also observed (Gendron 2002). Furthermore, a two months interval between a whale photo-recapture off Bahía Magdalena and San Quintín coincides with the slow movement of blue whales along the west coast of Baja California during their movement north (Gendron 2002).

Thus the current blue whale spatio-temporal distribution has apparently not changed much since Scammon's report in 1858. The similarity of past and present distributions off Bahía Magdalena and along the west coast suggests that this area might serve as stable spring and early summer feeding zones, in agreement with Reilly and Thayer (1990).

Blue whales are also found during all seasons in the offshore area of the Baja California west coast. They are observed during the spring, summer, and fall (Mangels and Gerrodette 1994, Gendron 2002). The same general area, offshore of the southern portion of the Peninsula, was characterized as a persistent concentration of temperature fronts called "hotspot" (Etnoyer *et al.* 2004) and where blue whales residence time, monitored through satellite tag, have permitted to identify presumed foraging area (Etnoyer *et al.* 2006).

5. FIN WHALE (*BALAENOPTERA PHYSALUS*), BRYDE'S WHALE (*BALAENOPTERA EDENI*), SEI WHALE (*BALAENOPTERA BOREALIS*), MINKE WHALE (*BALAENOPTERA ACUTOROSTRATA*)

Except for fin whales that appear to be rare off the west coast of Baja California (Scammon 1968, Rice 1974, Tønnessen and Johnsen 1982, Urbán and Aguayo 1985), the rest of the rorquals, the sei, Bryde's and minke whales have been reported (Rice 1974, Urbán and Aguayo 1985) or captured (Tønnessen and Johnsen 1982). For all species however, no winter ground has been described and very little is known about their movement, aside the information of whale marking- recovering effort made in the 60's by Rice (1974). The presence of Bryde' s whales from Bahía Magdalena south, along the west coast appears to be more notorious (Rice 1974) especially during fall (Gendron unpublished data), and could be associated with whales moving off the Gulf of California following sardines (Chávez-Rosales 1995, Urbán and Flores 1996).

6. NORTH PACIFIC RIGHT WHALE (*EUBALAENA GLACIALIS*)[1]

In contrast with the other species of baleen whales previously considered here, the Northeastern Pacific right whale is the most endangered population of large whales. Although this species has been intensively harvested, their breeding area has never been identified (Scammon 1968). It is believed that the number is probably in the tens and that the western coasts of the United States and Mexico were ever highly frequented habitat for this species (Brownell *et al.* 2001, Clapham *et al.* 2004). However, three of the very few reported sightings during the past century were made off the Baja California coast, including a recent sighting off San Jose del Cabo in February 1996 (Gendron *et al.* 1999). Historically, some were captured as far south

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[1] Now considered a separate species *Eubalaena japonica* http://www.iucnredlist.org

as Bahía San Vizcaíno between February and April (Scammon 1968). An extensive research on historical distribution based on the Maury charts concluded that the north Pacific right probably did not breed in coastal areas (Scarff 1986, 1991). However, the absence of searching effort along the Baja California west coast indicated by the Maury charts (Gendron *et al.* 1999) does not allow clarifying if right whales were using or not this area during winter.

7. SPERM WHALE (*PHYSETER MACROCEPHALUS*)

The largest tooth whale, the sperm whale, was perhaps the first species of whales to have been captured along this coast. During the sperm whales whaling era, the southern half of the Baja California west and south of the Peninsula were known as good whaling sites (Townsend 1935). More research would precise the importance of the area through the reviewing of the whaling log books from voyages accounts, such as the one made by Mitchell (1983) who showed that the area was visited. An interesting seasonal movement is observed in the Townsend maps by the presence of the whales in different areas in different seasons. Scammon (1968) also cited that sperm whales were found and captured in water depth as shallow as 60 fathom in the area between San Bartolome (now called Bahía Tortuga) and Point Abreojos (now called Punta Abreojos). Rice (1974) report only one sighting of 2 large male sperm whales along the coast. In the offshore areas of southern part of the Peninsula, sperm whales are reported there from June to October (Mangels and Gerrodette 1994, Gendron, unpublished data). Not much is known about the movement of these sperm whales there, although we suspect they might also visit the Gulf of California where they have been seen year round (Gendron 2000) and where several studies based on distribution, stable isotopes analysis and acoustic scattering layers suggest they feed on the jumbo squid (Jaquet and Gendron 2002, Ruiz-Cooley *et al.* 2004, Gallo-Reynoso *et al.* 2009). They also show high percentage of calves and mature males which suggest the area as a breeding, calving, and nursing ground (Jaquet *et al.* 2003).

In accordance with the IUCN Red List of Threatened species (http://www.iucnredlist.org) due to the poor information on most of the rorquals, Bryde's and minke whales are categorized as data deficient, but the sei whale as endangered. The gray and humpback whales have been re-categorized from vulnerable to the category least concern, the sperm whale as vulnerable, and the blue whale has been download from vulnerable to endangered, principally due to the very slow recovering of the overall species. However, the northeastern Pacific population is apparently increasing (Baskin 1993, Barlow 1994) and it is clearly considered the most recuperated of all populations. So aside the endangered North Pacific right whale, it come into view that several species are showing signs of recovery compared to the western north Pacific subpopulation/population and also from population from other oceans such as the North Atlantic with the extinct gray whale population (Barnes and McLeod 1984), and slow recovering blue whale population (Sears and Calambokidis 2002).

8. SUMMARY AND ANALYSIS OF THE AREA

The coastal area of the Baja California west coast, is used by all the migrating species of large whales and represent, 1) a breeding area for the gray whales, 2) a corridor between feeding and breeding areas for the mainland and Baja California humpback whales, 3) a seasonal feeding area for blue whales, and 4) an area of distribution of the North Pacific right whales, the Bryde's, sei, and minke whales. While this relatively non developed coast still provides a good quality habitat for these species, it should be protected from gillnet fishing at least seasonally during the migrating period (December to July). Although there are no database records of whale entanglement in the Mexican Pacific, it appears that there is at least one incident of a whale (usually a humpback whale) entangled in a gill net every year.

Another anthropological impact on whales to be avoided is the inappropriate whale watching activities. Aside the study on the whale-watching impact on gray whale in a feeding area off Canada (Duffus 1996) or during their migration off Ensenada (Heckel 2001, Heckel *et al.* 2001), little information is available in the breeding lagoons, where the most intense whale-watching activities occurs. Regulation of whale-watching should be promoted particularly in non protected areas such as Los Cabos region before it become a real problem as it is reported for Bahía Banderas, a well known aggregation area of the mainland humpback whales (Guerrero-Ruiz *et al.* 2006).

In accordance to Etnoyer *et al.* (2004), the offshore area off the southern portion is, 1) an important foraging area for blue whales and probably also for Sperm whales, and 2) a corridor for the migrating Humpback whales that winter off the Revillagigedo islands and should be promoted as a marine protected area.

9. CETACEAN STRANDING SURVEYS: A GOOD ILLUSTRATION OF SPECIES PRESENCE AND SEASONALITY ALONG A PORTION OF THE BAJA CALIFORNIA WEST COAST

Despite the ecological importance of the area, little is known about the community structure of small cetaceans. The lack of estimates in diversity, abundance and temporal occurrence of these marine organisms represent clear gaps in our knowledge. These gaps can be partially filled with information obtained by stranding records in land when the information in water is scarce or absent.

To illustrate how cetacean stranding data are useful to gather information on the populations that use the coastal area of the Peninsula, an analysis was made of the stranding data from a systematic survey conducted weekly along the beach of Magdalena Island (CICIMAR research project SEP-CONACyT 46806), a long sandy bar of 55 km in length located in the Bahía Magdalena lagoon complex (see Figure 1).

These three year surveys (2003–2006) allowed to identify a natural seasonal rhythm of cetacean strandings associated with natural processes occurring within the ecosystem with higher incidences in the late spring and early summer months (April, May, June and July), coinciding with the seasonality of the highest rates of net primary production in the area (Mercuri 2007). Based on these results, a schematic model of the seasonal evolution of significant ecosystem events adjacent to Magdalena Island was performed, showing that the upwelling process gives place to the development of primary productivity, followed by an increment in sardine abundance and finally the maximum incidence of strandings of high trophic marine mammals (Mercuri 2007). The correspondence of marine mammal abundance in the coastal area with the incidence of strandings was previously proposed by several authors (Mead 1979, Woodhouse 1991, López *et al.* 2002, Evans *et al.* 2005).

This research also produced baseline information for cetacean diversity in this region, with twelve cetacean species identified: 9 odontocetes and 3 mysticetes (see Table 1), which represents 38% of the thirty-two cetacean species reported for the Mexican Pacific Ocean (Aurioles Gamboa 1993). The most abundant group was composed of species that belongs to the subfamily Delphininae, including small size dolphins that mainly prey on small schooling fish such as sardines. Of these species, the common dolphins were the most abundant, particularly the long-beaked common dolphin (*Delphinus capensis*), recorded only during spring and summer with a maximum peak in June; coinciding with high sighting numbers off Magdalena Bay also in June (Valles Jiménez 1998). The next in abundance were the bottlenose dolphins (*Tursiops truncatus*) stranding principally during spring and summer. Although two ecotypes are recognized: the coastal and the oceanic (Walker 1981), no differentiation were made in the stranding records. The Pacific white-sided dolphin (*Lagenorrynchus obliquidens*), a temperate species that uses the coast of Baja California and occasionally the southern Gulf of California as its southern distribution boundary, was also recorded in the stranding surveys. This species is well known to move north-south and inshore-offshore in relation with the temperature

TABLE 1. Cetacean species identified in the strandings, proportion and seasonal occurrence along the Magdalena Island (species marked with a * belongs to the subfamily Delphininae).

Species	% frequency	Month
Non identified dolphin	38	From January to September
*Delphinus capensis**	23.1	From March to September
*Tursiops truncatus**	10.6	From February to September
Delphinus sp.*	9.1	From April to August
*Delphinus delphis**	8.7	From May to August
*Lagenorhynchus obliquidens**	4.3	January, May, July and August
*Stenella longirostris**	2.4	January and March
Eschrichtius robustus	2	January and February
*Grampus griseus**	0.5	October
Globicephala macrorhynchus	0.5	July
Mesoplodon peruvianus	0.5	August
Physeter macrocephalus	0.5	July
Balaenoptera sp.	0.5	May
Megaptera novaeangliae	0.5	December

of the water and the distribution of its preys (Leatherwood *et al.* 1984), so it is not strange that we found this species during the most productive season. In contrast, a pan-tropical species characteristic of warm water, the spinner dolphin (*Stenella longirostris*), occurred once in winter.

The rest of the strandings consisted of pelagic species that generally prey on squid, such as the pygmy beaked whale (*Mesoplodon peruvianus*), Risso's dolphin (*Grampus griseus*), pilot whale (*Globicephala macrorhynchus*), and the sperm whale. In the group of mysticetes, we registered an unidentified rorqual that was in high state of decomposition, made it difficult to identify the species. Judged by the size, the individual could be one of the three rorquals similar in morphology, the fin, sei or Bryde's whales. Two gray whales and one humpback whale were recorded during winter, and are clear examples of how the strandings are good indicators of residence and migration patterns (Moore *et al.* 2003). Each of these species appeared only one or two times in the stranding records.

In several of the fresh strandings, the animals showed marks caused by human interaction (net or chain marks, entanglement with nets or fluke mutilation with a knife). The gray whale migrating along the proximity to the coast is particularly vulnerable to get entangle in fishing nets and being struck by ships or panga. There are several examples of these incidents in Mexico (Urbán *et al.* 2003), mainly during the winter season, when the whales are inside the lagoons and the small fiberglass fishing boats (pangas) occasionally hit them during the transit to the fishing areas outside the lagoons.

However, the evidences of these incidents (entanglement and ship strike) are hard to distinguish in the carcasses of the animals. The factors that could influence in the detection of signs of human interaction are: 1) marks of entanglement are difficult to detect in decomposed specimens, they usually have lost the skin or it has been burned by the sun; 2) some animals are founded after scavenger animals had preyed on, so they lost parts of the body that should have been examined; and 3) the training of field staff to identify marks usually gets better over time with the experience.

Bahía Magdalena is the most important fishing ground for artisanal fisheries in the state of Baja California Sur (Carta Nacional Pesquera 2004). There are several fishing gear types that are used in the area, but the most dangerous or threatening to marine mammals are those used in the scale fish fishery (gillnets) during May to September. Little is known about the fisheries that operates in the offshore region of Bahía Magdalena, where larger fleet (ships of 45 feet in length or more), that principally focused in shark fishing, use 2000 m of drift gillnets or 20 km of longlines with 700 hooks (Rivera 2004). These activities and possible interactions with cetaceans should not be underestimated.

Although there are few published estimates of the magnitude of incidental capture (bycatch) in marine mammals, it is known that the consequences are likely to have demographic effects that might significantly threaten many marine mammal populations (Read *et al.* 2006), therefore, more and better data to understand the impact of these interactions are required. Strandings, in this context, are a useful tool to estimate at least a minimum rate of mortality due to anthropogenic interaction.

The continental shelf region of the west coast of Baja California has a vast amount of natural resources that are poorly exploited in the present, however, considering the great potential of the fisheries it is not difficult to assume that more extraction will be promoted in the future (Lluch-Cota *et al.* 2006). And with this, certainly, more interactions with marine mammals will occur.

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SEABIRDS AND PELAGIC FISH ABUNDANCE IN THE MIDRIFF ISLANDS REGION

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Small pelagic fish are food for many marine species. We show that diet and reproduction of seabirds are coupled to oceanographic conditions. This information is used to predict the outcome of fishing efforts several months in advance of the onset of fishing season. The proportions of each fish species in the diet of three seabird species, were found to be closely correlated with those in the commercial catch. Seabirds were found to be much more sensitive than the commercial fleet to fluctuations in the abundance of these fish. In a long term demographic study of Heermann's Gulls, we found their fecundity rates change drastically from ENSO (El Niño) to non-ENSO ("normal") conditions. Simulation analyses under different ENSO frequencies showed a non-linear decline of the population growth rate as the ENSO frequency increases. The population can withstand frequencies as high as one ENSO every 5 years without suffering serious population declines; it will be relatively stable at frequencies of one ENSO every 4 years, but will decrease drastically at higher frequencies.

1. FORAGE FISH AS THE BASE OF THE PELAGIC MARINE FOOD CHAIN

One of the most productive marine areas of Northwest Mexico is the Midriff Island Region, in the Gulf of California (Álvarez-Borrego 1983) (see Figure 1). This area, located in the central Gulf of California, has a high marine productivity due to the strong upwelling induced by the islands and the tides, as well as the more common upwelling promoted by the wind action that is common along many of the coastal areas of the world and, particularly, along the coastal areas of the Gulf of California.

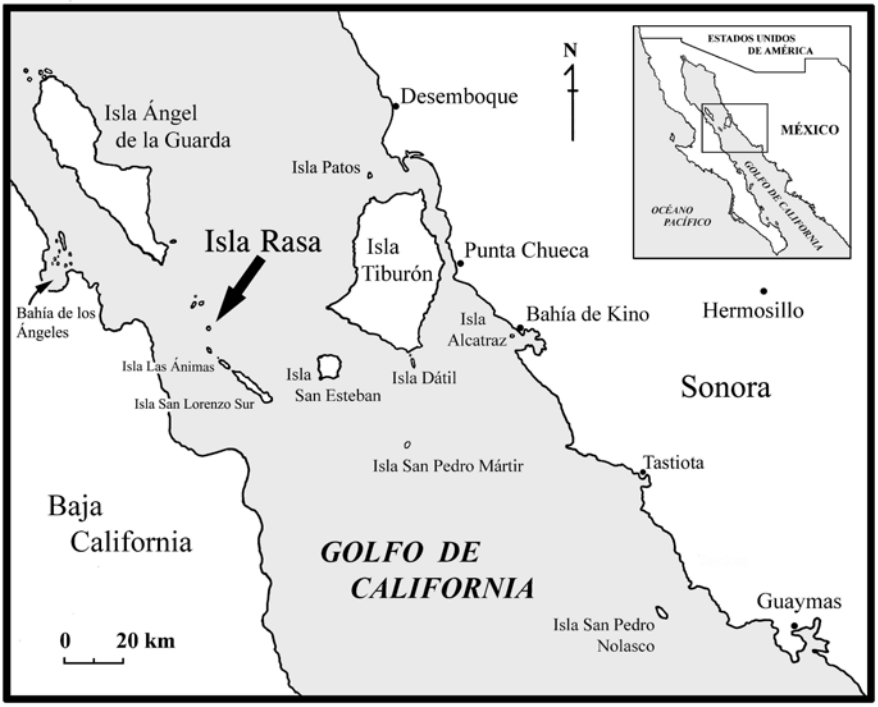

FIGURE 1. Southern section of the Midriff Island Region of the Gulf of California.

The tidal upwelling characteristic of this area adds up to the wind driven upwelling resulting in one of the highest marine productivities in the world. Important to this marine richness is also the extensive presence, at least until a few decades ago, of coastal lagoons and mangrove areas, which constitute superb nurseries for many marine species, be it invertebrates, fish, and also several aquatic bird species. As a consequence, the region's importance for many marine organisms is relevant on a worldwide scale. Seabirds are not the exception when one considers the high percentages of the total nesting populations of at least ten seabird species that occur in the region. Several waterbirds and shorebirds also nest on some of the Gulf of California islands (Anderson *et al.* 1976, Anderson 1983), and the area is also of great importance for the wintering and migration of many other species of these bird groups, such as geese and several duck species.

Offshore islands are some of the most important breeding areas for about 20 seabird species that are known to nest in the area, the most numerous of which are the Least Storm-petrel (*Oceanodroma microsoma*), the Heermann's Gull (*Larus heermanni*) (that nests almost exclusively in the Gulf and is, therefore, considered cuasi-endemic to the area), the Elegant Tern (*Thalasseus elegans*), and the Craveri's Murrelet (*Synthlyboramphus craveri*), all of which have close to 95% of their total populations concentrated in the Gulf during the nesting season; plus the Yellow-footed Gull (*Larus livens*), that is also considered cuasi-endemic to the Gulf (Anderson 1983, Velarde and Anderson 1994).

Conservation problems in the region are not small, including the impact of the large sardine fishing industry that flourished in this area. Historically, at a worldwide level, fisheries have been difficult to manage in a sustainable fashion, and many regional economies have been shaken by the collapse of their fisheries (Radovich 1982, WRI 1994, Botsford *et al.* 1997, Schwartzlose *et al.* 1999). Since the last couple of decades, the majority of the world's fisheries have been in a state of overexploitation, or nearly so, and that includes the small pelagic fisheries such as sardines and anchovies, which constitute close to 25% of total commercial landings (WRI 1994, Botsford *et al.* 1997). The populations of these fishes are characterized by wide population fluctuations, resulting from the effect of fluctuating oceanographic-atmospheric phenomena such as El Niño Southern Oscillation (ENSO). Due to their migratory nature, generally immense biomass, and wide mobility, their populations are hard to monitor, and it has been extremely difficult to obtain robust indicators of their abundance and availability to the commercial fleets (Schwartzlose *et al.* 1999, Sánchez-Velasco *et al.* 2000), thus the management decisions for their fishery have been primarily based on market rather than on biological information.

Small pelagic fishes are the basis of many important coastal marine ecosystems such as the rich California, Humboldt, and Benguela Current systems, and they form the main food source for a variety of larger fish, many of which are also economically important. Small pelagic fish are fundamental food items for marine mammal and seabird species (Anderson and Gress 1984, Burger and Cooper 1984, Furness 1984, MacCall 1984, Furness and Barrett 1991, Furness and Nettleship 1991, Montevecchi and Berruti 1991, Velarde *et al.* 1994, Sánchez-Velasco *et al.* 2000), and many studies have shown the value of seabird diet information as a tool to indirectly monitor the status of the fish species on which they feed, and have shown significant correlations between seabird diet and fisheries parameters (Anderson *et al.* 1980, Anderson and Gress 1984, Burger and Cooper 1984, Furness 1984, MacCall 1984, Berruti and Colclough 1987, Bailey *et al.* 1989, Martin 1989, Barrett 1991, Furness and Barrett 1991, Furness and Nettleship 1991, Montevecchi and Berruti 1991, Velarde *et al.* 1994, Crawford and Dyer 1995, Montevecchi and Myers 1995, Crawford 1998, Sánchez-Velasco *et al.* 2000).

The proportions of each forage fish species in the diet of three seabird species —California Brown Pelican (*Pelecanus occidentalis californicus*), Heermann's Gull and Elegant Tern—nesting in the Gulf of California, have been found to be closely

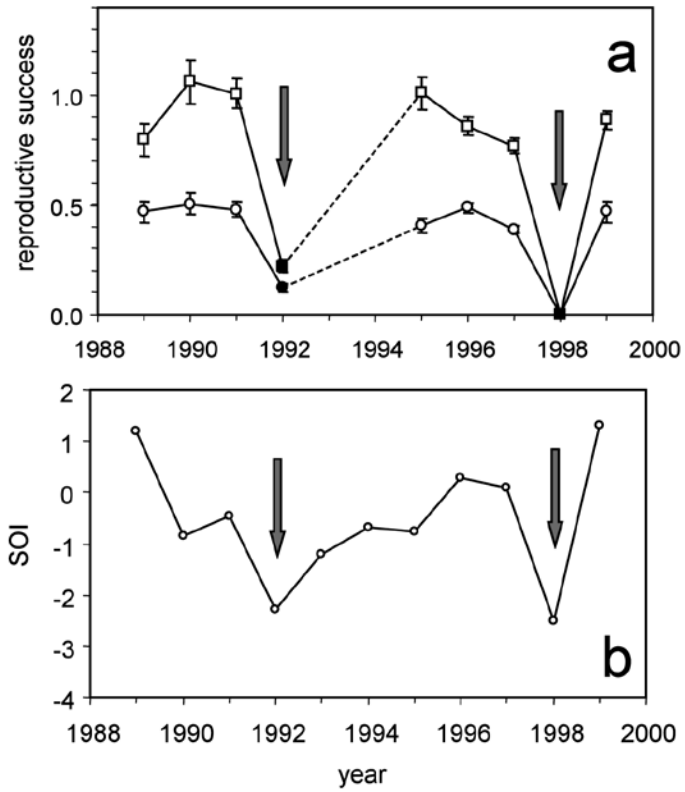

FIGURE 2. Effect of El Niño on seabird breeding success: (a) reproductive success of Heermann´s Gull in the Gulf of California between 1989 and 1999 (excluding 1993 and 1994, in which sampling was interrupted). Squares indicate number of fledglings produced per nest; circles indicate number of fledglings produced per egg laid (means ± 1 SE). (b) Values of the December-May mean Southern Oscillation Index (SOI) between 1989 and 1999. In both figures the arrows indicate years in which the mean December–May SOI reached extreme negative values (less than – 1.5). Taken from Velarde *et al.* 2004.

correlated with those in the commercial catch. However, seabirds have been found to be much more sensitive than the commercial fleet to fluctuations in the abundance of small pelagic fish in the environment (Velarde *et al.* 1994). This renders these seabirds as important indicator predator species of the status of the small pelagic fish populations and communities, a fact that is extremely useful for the decision making at the present at the present time, when effects of global warming are an everyday threat and economic decisions need to be made, taking into account the long term effects of human activity.

2. THE REPRODUCTIVE BIOLOGY OF SEABIRDS AND ITS RELATIONSHIP TO THE ABUNDANCE OF PELAGIC "FORAGE" FISH

In the case of most seabirds, parental age, body condition, and food availability have been found to strongly influence breeding parameters, such as clutch size, number of chicks hatched and fledged, hatching, fledging and reproductive success (Anderson *et al.* 1980, 1982, Sunada *et al.* 1981, Boekelheide and Ainley 1989, Penniman *et al.* 1990, Sydeman *et al.* 1991). In the Gulf of California for example, the main factors driving reproductive success in Heermann's Gull (a vulnerable species according to Mexican federal law) were found to be parental age and body condition (estimated by body mass), and food availability (estimated from Catch Per Unit Effort statistics for Pacific sardine (*Sardinops caeruleus*) + Northern Anchovy (*Engraulis mordax*) by the local fishing fleet) (Vieyra *et al.* 2009). From studies of this species (Velarde 1999, Velarde and Ezcurra 2002, Velarde *et al.* 2004, Vieyra *et al.* 2009) it was clear that breeding parameters showed their lowest values in ENSO years, in which the birds also showed significantly lower individual weights for both males and females. These years also were the ones when local CPUE of sardine + anchovies was lowest (Velarde *et al.* 2004, Vieyra *et al.* 2009) (see Figure 2).

A strong chained relationship was found between the different extrinsic variables such as food availability, which is strongly driven by oceanographic conditions, was found to strongly affect both parental body condition and the survival of eggs into hatchlings and the survival of hatchlings into fledglings, while intrinsic variables, such as parental age (the latter being a biological factor intrinsic to each nesting couple), was found to explain most of the observed between-nest variation in fledgling success, or the proportion of eggs laid by a nesting pair that produced flying young (Vieyra *et al.* 2009).

3. SUMMARY OF THE SMALL PELAGIC FISHERY IN THE GULF OF CALIFORNIA

As summarized in Cisneros *et al.* (1995), in the mid 1900's a small pelagic fishery fleet developed in the Mexican Pacific, along the western coast of the Baja California Peninsula. By the mid 1960's this fishery suffered from the natural fluctuations of oceanographic conditions (ENSO) on these fish populations, in combination with the overfishing that occurred during these years. As a result, the availability of these fish, particularly the Pacific sardine, species on which the fishery was based during the early years of its development, decreased drastically and the existing fleet was moved into the Gulf of California. This industry developed mainly targeting Pacific sardine, initially during the Winter months in the Guaymas basin, and later, when cooling systems were added to the fishing boats, extending to the Midriff Island Region during the Summer months, to initially unimagined levels, growing from a total sardine catch of some 11,000 metric tons in the 1969/70 fishing season, to almost 100,000 in the season 1980/81, almost an order of magnitude in a little over 10 years (Cisneros *et al.* 1995). This period of relatively slower growth was fallowed by another decade of higher growth rate, with a three fold increment in the catches between the latter and the 1988/89 season, reaching a catch of almost 300,000 tons. After that season the catches decreased by almost 100,000 tons and, two years later and in coincidence with the El Niño of 1992, the catches collapsed to around 7,000 metric tons for the next two seasons, a decrease of almost 98% of the record catch of 1989! Following this collapse the catches rapidly recovered, and in 5 years the sardine catches surpassed the 200,000 metric tons, but collapsed again to less than 60,000 in the 1997/98 season, only to recover and collapse once more in the 2001/02 and 2004/05 seasons, respectively, to less than 100,000 tons. Although a clear relationship between the collapses of the catch and the occurrence of the El Niño phenomenon could be observed, a brief analysis of the catch per unit effort (Velarde *et al.* 2004) revealed that, while until 1989 the catches increased in significant correlation with the fishing effort of the fleet, after that year the catch remained independent of the effort, a clear sign of overfishing. Regardless of this, the effort of the fleet was not reduced and between the latter and the 2007/08 season the catch reached another record catch of almost 500,000 metric tons of Pacific sardine, and over that figure in the following season, the highest catch of all its history (see Figure 3).

During the breeding season of 2008 the breeding success of all the seabirds in Isla Rasa was high and feeding frenzies could be observed almost every day right off the island's shores. However, during the 2009 season, the number of nesting Elegant Terns that established in the island were close to 30% of the total normal population, and all abandoned the nesting colony before incubation completion. For the Heermann's Gulls, only about 60% established a nesting territory, and it is not known if a larger fraction of the population arrived to the nesting grounds but was not guarding their territories. Of the gulls that were seen in their territories, only 40% laid at least one egg, but the average clutch size was much smaller than that of "normal" years (1.42 in 2009 and 2.16 average 2000–2008). This is if we consider only the nests where at least one egg was laid. However, if we consider all the nests in the sample, the average clutch size drops to 0.78 eggs per nest. Of the few Heermann's Gulls that laid eggs, even fewer were able to finish incubation, because many abandoned the nest to feed before the mate returned to relieve them, as it is done during

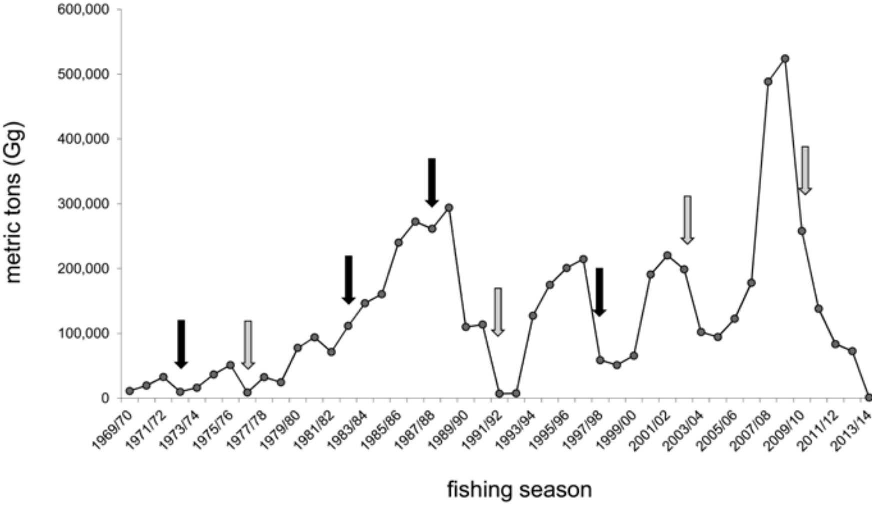

FIGURE 3. Trend of the Pacific Sardine catches by the fleet of the State of Sonora, Mexico in the Gulf of California. Black arrows indicate strong El Niño thermal anomalies, gray arrows show mild El Niño anomalies. Catch information taken from: http://www.inapesca.gob.mx/portal/documentos/publicaciones/Anexo1_InfTec_CaptEsfuerzoFlota_PMGC.pdf

"normal" years. Finally, most of the scant number of hatched chicks died when their parents abandoned them to go to sea in search of the scarce fish that remained in the area, so the breeding success for that breeding season was 0.1 chicks per nest, instead of the average of 1 chick per nest during "normal" years.

4. THE VALUE OF THE INFORMATION ABOUT SEABIRD BIOLOGY TO PREDICT FISHERIES SUCCESS

As mentioned above, small pelagic fish at present constitute 25 to 40% of the fisheries landings in Mexico. Over 70% of these landings, predominantly Pacific sardine (*Sardinops sagax*), are captured in the Gulf of California. Small pelagic fishes are a key component of the Gulf's ecosystem, since they are eaten by seabirds, sea mammals and other fishes. The sardine fishery within the Gulf has been showing signs of overfishing since the early 1990s.

Statistical models show that oceanographic conditions and seabird breeding and feeding data can accurately predict total fishery catch and catch per unit effort (CPUE) of Pacific sardine in the central Gulf of California (Velarde *et al.* 2004). Total catch has been predicted with an accuracy of 54% by a linear model incorporating the Southern Oscillation Index (SOI), the clutch size of Heermann's Gulls, and the proportion of sardine mass in the diet of Elegant Terns. Moreover, CPUE has been predicted with an accuracy of 73% by a model based on the proportion of sardines in the diet of Elegant Terns, the reproductive success of Heermann's Gulls, and the springtime sea surface temperature anomaly in the Gulf region (Velarde *et al.* 2004). Several studies have shown that reproductive ecology of seabirds is coupled to the global and local oceanographic conditions, and that this information can be used to predict the outcome of fishing efforts with several months in advance of the onset of the fishing season (Velarde *et al.* 1994, 2004, in press). Models of this kind are very useful and can provide key information for fisheries administrators and the industry, to make decisions to reduce the effort (and expenses) of the fleet in years when it can be anticipated that CPUE will be low.

5. THE VULNERABILITY OF THE MIDRIFF ISLAND ECOSYSTEM TO LARGE-SCALE OCEANOGRAPHIC ANOMALIES AND THE MANAGEMENT OF ITS NATIVE SPECIES

As it was found in a demographic study based on long term records of the banding, survival and breeding of the Heermann's Gulls nesting in Isla Rasa, their fecundity rates change drastically from ENSO (El Niño) to non-ENSO ("normal") conditions. A matrix-based demographic analysis of their population growth under the two situations predicted close to a 2% annual population growth during normal years, and a rapid decline (-15%) under sustained ENSO conditions. Under non-ENSO conditions fecundities contribute more to population growth rate than survival, but under ENSO conditions survival is the key demographic factor (Vieyra *et al.* 2009). Simulation analyses under different hypothetical frequencies of El Niño anomalies showed a gradual but non-linear decline of the predicted growth rate as the ENSO frequency increases. All other factors being as they presently are, the Heermann's Gull population can withstand frequencies as high as one ENSO event every 5 years without suffering a serious population decline; the population will be relatively stable at frequencies of one ENSO event every 4 years, but will decrease drastically at higher frequencies (see Figure 4). This shows us that the longevity of seabirds seems to be an evolutionarily selected trait in response to the fluctuating environmental conditions that characterize many coastal ecosystems, and the past existence of drastic fluctuations in the availability of pelagic fish.

Heermann's Gulls seem to be well adapted to these fluctuations and are able to resist relatively high frequencies of oceanographic anomalies, without seriously compromising, neither their population growth rate, nor their individual fitness.

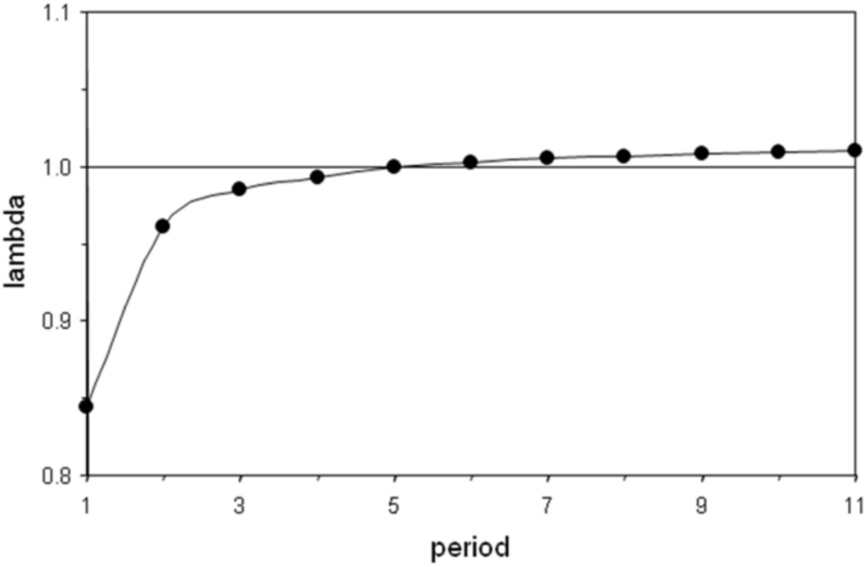

FIGURE 4. Long-term population growth (λ) for Heermann's Gull under different frequencies of occurrence of the ENSO phenomenon (a period of 1 indicates an El Niño event every other year, and so on). Taken from: Vieyra *et al.* 2009.

However, their populations may decline rapidly if warm-phase anomalies increase in frequency in the future as a result of global ocean warming, or if sardine overfishing puts the availability of their food sources at risk. If we believe that other species inhabiting the area have similar adaptations, and consider the effects analyzed here extended to the rest of the ecosystem, the increase of the frequency of the warm phase anomalies may result in severe imbalances through the food chain and drastic consequences to the whole ecosystem, particularly if extractive activities enhance the effects of the natural ones.

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DISTRIBUTION OF CHAPARRAL AND PINE-OAK "SKY ISLANDS" IN CENTRAL AND SOUTHERN BAJA CALIFORNIA AND IMPLICATIONS OF PACKRAT MIDDEN RECORDS ON CLIMATE CHANGE SINCE THE LAST GLACIAL MAXIMUM

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Chaparral, the evergreen sclerophyllous scrub characteristic of the mediterranean-climate region of North America, grows extensively in dense stands from northern California to lat. 30°N, but thins to a few isolated populations or "sky islands" on the highest mountains in the Central Desert of Baja California (~30°–27.5° N lat.), as well as on the highlands of Isla Cedros. Chaparral also occurs in small outlying populations at lower elevations in the Central Desert, and as understory in tropical thorn scrub and montane Mexican pine-oak woodland, extending nearly to Cabo San Lucas. We present the first detailed maps of chaparral populations in the north central and Mexican pine-oak woodlands in the southern Peninsula, interpreted from Google Earth™ imagery and herbarium databases. We also compare the present distribution of chaparral with available records from Pleistocene–Early Holocene packrat middens. We show that chaparral is unexpectedly widespread in the Central Desert and propose, on the basis of the cistern effect of bedrock surfaces of midden sites and the physical equatorward limit of jet stream precipitation, that climate change since the Last Glacial Maximum was not as pronounced as has been suggested in studies of packrat middens.

1. INTRODUCTION

The equatorward limit of mediterranean-type climate and evergreen sclerophyllous scrub lies near the 30th parallel on continental west coasts throughout the world, including Baja California (Mexico), central Chile, South Africa, southwest Australia, and the southern Mediterranean basin (Bahre 1979, Heusser 1994, Rundel *et al.* 1998, Minnich and Franco-Vizcaíno 1998, Dean and Milton 2000, Vaks *et al.* 2006).

This limit reflects the equatorward extent of reliable winter precipitation associated with frontal cyclones of the polar-front jet stream. In summer, the jet stream is poleward of mediterranean regions, and protracted drought is facilitated by suppressed convection over cold, upwelling ocean currents and their associated marine stratus layers. Equatorward of the 30th parallel, precipitation is unreliable year-round, and mediterranean scrub is replaced by desert vegetation.

On the Pacific coast of North America, mediterranean chaparral extends from northern California (USA) to the Sierra San Pedro Mártir at lat. 30°N in Baja California (Minnich and Franco-Vizcaíno 1998). To the south, small mountain chains in the Central Desert with summit elevations >1,500 m and Isla Cedros have "sky islands", or isolated stands, of chaparral (Bullock *et al.* 2008) to as far south as 27.5°N. In the Central Desert, areas that host chaparral are characterized by locally cooler climate and orographic winter precipitation. Even farther south, chaparral species occur in thorn scrub and montane Mexican pine-oak woodlands that grow in summer rain climates of the North American monsoon nearly to Cabo San Lucas (lat. 23°N), similar to that in the mountains of mainland Mexico (see *e.g.* Minnich *et al.* 1994).

Knowledge of the history of Baja California vegetation since the Last Glacial Maximum (LGM, ~20,000 years before present) is critical to understanding the origins of chaparral "sky islands", as well as the deep-time processes responsible for plant diversity and endemism in the Peninsula (Wiggins 1980, Case and Cody 1983). Packrat middens dating to the Late-Pleistocene show that chaparral grew at lower elevations and farther south than at present (Wells 2000, Rhode 2002, Metcalfe 2006, Minnich 2007, Holmgren *et al.* 2011). Using a "vegetation analogy" method, midden studies deduce major climate shifts in the Central Desert based on macrofossil evidence and lake stands.

The evaluation of chaparral biogeography since the LGM requires baseline data of its present distribution and species composition. While botanical collections have described the chaparral flora in the Central Desert, vegetation maps are another source of biotic data for the interpretation of fossil packrat middens and paleoclimate. Chaparral in Baja California has been mapped as far south as lat. 30°N (Minnich and Franco-Vizcaíno 1998), but the distribution of chaparral sky islands in the Central Desert and pine-oak woodlands in the southern Peninsula has not been inventoried in detail. In this study, we conducted a comprehensive inventory of the Baja California Peninsula south of lat. 30°N, and used Google Earth™ imagery to produce the first maps of chaparral sky islands and Mexican pine-oak woodlands that contain chaparral understory, and utilized previously published data and herbarium databases to determine species composition. We compare modern chaparral with chaparral records in Pleistocene–Early Holocene packrat middens (Wells 2000, Rhode 2002, Holmgren *et al.* 2011), and evaluate the unusual lithology, hydrology and vegetation of midden sites. Finally, we argue from first principles in atmospheric science that moist climates in the past were largely due to cooler temperatures, not increased precipitation, as seen farther north in the USA. We show that local populations of chaparral are unexpectedly widespread in the Central Desert and suggest that climate change since the Last Glacial Maximum, in particular total precipitation was not as large as has been proposed in packrat midden studies.

2. METHODS

2.1. Study area

We define the Central Desert as the region from the southern Sierra San Pedro Mártir (lat. 30.5°N) to San Ignacio in Baja California Sur (lat. 27.3°N). South of lat. 30°N the peninsular range—the region's mountainous backbone—includes a series of discontinuous ranges that parallel the Gulf of California (see Figure 1; all figures on pp. 279–290). The mountains comprise broad plateaus, with steep fault escarpments toward the Gulf, and westward-dipping slopes that grade into alluvial plains toward the Pacific. Mountain crests range from 1500 to 1932 m and include the Sierras La Asamblea (lat. 29.4°), La Libertad (28.8°), San Francisco (27.6°), La Giganta (27–25°), Las Cruces (24.1°) and La Laguna (23.5°), as well as Volcán Las Tres Vírgenes (27.5°) and Isla Cedros (28.2°). Coordinates of place names are given in Table 1.

From the Sierra La Libertad northward, the mountains consist mostly of exposed plutonic bedrock of the Cretaceous peninsular range batholith, with local caprock of Tertiary volcanics and prebatholithic metasedimentary and metamorphic rocks (Gastil *et al.* 1975, INEGI 1988). Extensive post-batholithic volcanics, ranging from Miocene age to recent, are exposed from Cataviña to west of the Sierra La Asamblea, an area of numerous dry lake beds and playas, such as Laguna Chapala. In the southern peninsula, south of San Ignacio, the region from the Sierra San Francisco to the Sierra La Giganta comprises mostly Tertiary volcanics. Intrusive rocks of the peninsular batholith also dominate the mountains of the cape region.

The Baja California Peninsula presents one of the world's clearest Mediterranean-tropical transitions, with essentially uniform mean annual precipitation and temperature across the Central Desert, but an increasing proportion of summer precipitation towards the south (see Table 2). North of latitude 30°, the climate in the coastal plains and mountains of Baja California is Mediterranean with winter precipitation and summer drought. From the Sierra San Pedro Mártir northward, the orographic

TABLE 1. Location of place names (degrees, decimal minutes).

Location	Latitude N	Longitude W
Arroyo El Encinal near Cerro Loreto	26 6.0	111 36.0
Arroyo El Horno near Cerro Loreto	26 4.2	111 34.8
Arroyo Las Palmas	29 19.2	114 6.0
Arroyo Zamora	29 51.6	114 40.2
Bahía San Cristobal	27 25.0	114 30.0
Bahía Tortugas	27 43.2	114 54.0
Catavíña	29 45.6	114 43.8
Cerro "1590"	27 34.2	113 1.8
Cerro "1063"	28 16.8	115 12.6
Cerro El Alguatosa	29 49.8	114 36.3
Cerro La Borreguera	28 48.0	113 36.0
Cerro La Libertad	28 51.6	113 36.6
Cerro La Sandia	28 24.4	113 26.3
Cerro Loreto	26 6.0	111 34.8
Cerro Los Pocros	26 39.0	112 7.8
Cerro Matomí	30 22.3	115 7.1
Cerro Pedregoso	29 35.4	114 30.0
Cerro Redondo	28 7.8	115 13.2
Cerro San Juan (C. La Bandera)	27 59.0	112 59.0
Cerro San Luís	29 22.0	114 5.4
El Progreso	29 58.2	115 12.0
El Rosario	30 4.2	115 42.0
Laguna Chapala	29 22.2	114 21.0
Laguna San Felipe (L. del Diablo)	31 7.8	115 16.8
Mesa Catarina	28 30.0	113 46.2
Mesa Corral Blanco	28 26.4	113 46.2
Mesa El Gato	29 34.4	114 36.1
Mesa El Mármol	29 57.0	114 45.0
Mesa El Salado	29 16.0	114 18.6
Mesa San Carlos	29 42.0	115 27.0
Mesa Santa Catarina	29 39.6	115 19.2
Misión San Fernando	29 58.2	115 14.2
Misión Santa Gertrudis	28 3.6	113 4.8

Location	Latitude N	Longitude W
North Point Isla Cedros	28 22.2	115 13.2
Punta Baja	29 57.0	115 48.6
Punta Canoas	29 25.6	115 11.2
Punta Eugenia	27 51.6	115 5.0
Punta Prieta	28 48.6	114 23.4
Santa Catarina Sur, summit 14 km NE	29 48.4	115 0.87
San Juan Mine	28 45.0	113 35.4
Santa Inés	29 43.7	114 41.7
Sierra Agua Verde (S. Cantil Blanco)	26 54.0	112 21.0
Sierra Las Cruces (S. Las Canoas)	24 6.0	110 7.2
Sierra La Laguna	23 31.8	109 57.0
Sierra San Pedro (S. La Giganta N)	26 57.0	112 27.0
Sierra San Pedro Mártir	31 0.0	115 30.0
Vizcaíno Peninsula	27 42.0	114 42.0

lift of frontal storm air masses from the North Pacific Ocean over continuous high terrain assure a reliable winter rainy season. To the south, storm air masses yield little orographic precipitation, due to the low elevation of the mountains (average annual precipitation < 30 cm). The entire peninsular range experiences summer thunderstorms of the North American monsoon. The heaviest summer precipitation occurs in the Sierra La Laguna, then decreases northward along the Sierra La Giganta to a minimum in the Sierra La Asamblea, then increases again in the Sierra San Pedro Mártir (see Table 2). In late summer, tropical cyclones of the east Pacific enter the Cape Region almost annually, decreasing to only once per decade in the northern Central Desert (Smith 1986). Mean annual precipitation ranges from 40–70 cm in the Sierra San Pedro Mártir (Franco-Vizcaíno *et al.* 2002), and is likely 20–35 cm at higher elevations in the low sierras of the Central Desert, 30–40 cm in the Sierra La Giganta (see Table 2), and 40–70 cm in the Sierra Laguna.

With the advantage of year-round photosynthesis, evergreen chaparral grows in spring, when temperatures warm under moist soil, and survive summer drought with sclerophyllous foliar metabolism, and by rooting deep into bedrock fractures with secure water in regolith (Hubbert *et al.* 2001a, 2001b, Witty *et al.* 2003). During drought, stomatal closure reduces photosynthetic rates, but this is compensated by efficient canopy maintenance (Keeley and Davis 2007). High foliar lignin, shrub morphology, and the "carpet" structure of chaparral (contiguous horizontal and

TABLE 2. Selected climatological data for the central and southern Baja California Peninsula (calculated from Reyes Coca *et al.* 1990, and Miranda *et al.* 1991).

Name of weather station and elevation in meters	Lat. N° "	Long. W° "	Nearby Sierra	Mean Temperature (°C)			Mean Precipitation (cm)	
				Jan	Jul	Annual	Annual	% Jun-Sep
Rancho Santa Cruz 1000	30 54	115 36	San Pedro Mártir	10.4	24.9	16.7	30.5	17
El Progreso 517	30 0	115 12	San Pedro Mártir	13	26.1	18.7	13.7	16.8
San Luís (Sta. Inés) 510	29 42	114 42	La Asamblea	13	26.6	19	11.3	18.4
Laguna Chapala 640	29 24	114 24	La Asamblea	10.9	25.4	17.6	12.5	21.8
Punta Prieta 217	28 54	114 12	La Libertad	17.6	25	19.7	11.2	15.3
San Borja 412	28 42	113 42	La Libertad	15.1	25.3	19.9	13.7	24.6
San Regis 495	28 36	113 48	La Libertad	14.2	25.1	19.3	13.8	23.2
Rancho Alegre 120	28 18	115 54	La Libertad	14.6	24.8	19.4	14.9	21.9
Santa Gertrudis 400	28 6	113 6	San Francisco	15	27.5	20.4	13.7	52.1
El Arco 300	28 0	113 24	San Francisco	16.5	26	20.8	11.9	35
Díaz Ordaz 70	27 48	113 24	San Francisco	13.7	23.9	18.6	10.3	34.3
Bahía de Tortugas 16	27 42	115 0	Vizcaíno Peninsula	15.4	22.3	18.9	9.3	17.2
San Ignacio 110	27 30	112 48	Las Tres Vírgenes	13.6	24.7	19.2	9.75	45.9
San Zacarías 125	27 12	112 48	La Giganta (S. Pedro)	15.2	23.7	19.2	9.79	41.8
San José Comondú 270	26 6	111 48	La Giganta	16.6	27.2	21.7	17	53.9
Tepentú 160	25 6	111 12	La Giganta	15.8	27.4	21.4	11.6	67.9
La Soledad Norte 340	24 48	110 48	La Giganta	15.2	26.2	21.8	24.1	67.3

Name of weather station and elevation in meters	Lat. N° "	Long. W° "	Nearby Sierra	Mean Temperature (°C)			Mean Precipitation (cm)	
				Jan	Jul	Annual	Annual	% Jun-Sep
El Cajoncito 78	24 12	110 12	Las Cruces	16.7	26.8	21.8	21.6	64.9
Sierra La Laguna 1800	23 30	110 0	La Laguna	7.7	16	12.2	67.3	73.2
Cabo San Lucas 45	22 54	109 42	La Laguna	18.6	27	23	21.6	64.9

vertical fuel continuity) encourage recurrent stand-replacement burning (Minnich and Chou 1997). Cumulative build-up of live canopy and increased leaf area contributes to desiccation and canopy flammability. Chaparral responds to fire by resprouting and mass recruitment from seed banks (Keeley and Davis 2007). Fire intervals are in the order of two events per century in the Sierras Juárez and San Pedro Mártir, where there is little effective fire control (Minnich and Chou 1997, Minnich *et al.* 2000). Pine-oak forests are dominated by deciduous oaks with mesophytic foliage. Trees respond rapidly to summer rains that coincide with high temperature, but experience leaf drop in response to winter drought.

2.2. Interpretation of chaparral vegetation in Google Earth imagery

We inventoried chaparral "sky islands" and Mexican pine-oak forests by using high-resolution Digital Globe and other imagery of Google Earth. Imagery was examined by graduated scaling, the zoom function allowing for the observation of broad-scale patterns of vegetation and terrain (at small scales), and near-ground (large scale) identification of vegetation features. Species ranges were delimited in KMZ files using the digitizer function of Google Earth. Maps of chaparral sky islands and Mexican pine-oak forest were developed by digitizing directly onto Google Earth imagery (Minnich *et al.* 2011a). Chaparral and Mexican pine-oak woodland were identified on the basis of morphology, stature and color. Species composition was determined by consulting databases of botanical collections at the San Diego Natural History Museum (SDNHM), the University of California, Riverside herbarium, the Flora of North America (eFloras 2010), and Wiggins (1980).

Google Earth imagery was scanned comprehensively in an "X-Y" format, including extensive areas where chaparral and forests are not found, to ensure that outliers were not omitted. Imagery was examined at the smallest possible scale consistent with resolution of trees and shrubs (*ca.* 1,500 m above-ground), to maximize the efficiency of scanning. When a population was suspected or encountered, Google Earth was scaled to 600 m above-ground to confirm identification. Closer inspection was not possible due to pixelation of imagery. Although Google Earth imagery is monoscopic, the tilt feature was used for three-dimensional viewing of terrain and rock-substrate properties. Imagery was examined by looking "north-to-south" (south to top), in order to observe tree morphology independently of shadows; that is, to avoid the repetition of images of crowns and shadows that result from viewing towards the north. By looking south, shadows extend toward the bottom of the image and can thus be ignored. In order to distinguish between evergreen chaparral and deciduous species, multiple images taken at different seasons were examined. Chaparral and Mexican pine-oak woodland were defined at ~10% cover.

Imagery was examined online between August 2007 and August 2009. The database digitized on Google Earth was saved in the compressed version (kmz) of the keyhole markup language (kml) and placed into a compressed format. The file was subsequently saved in uncompressed (kml) format and converted to a standard GIS vector format, using ESRI ArcGIS Desktop 9.1 operating under an ArcInfo license (Environmental Systems Research Institute, Inc. 2010). Data were converted from the kml format to a feature classes ("shape") file for use in ArcGIS.

3. DISTRIBUTION AND SPECIES COMPOSITION OF CHAPARRAL "SKY ISLANDS"

Chaparral covers the four highest sierras of the Central Desert, and the highlands of Isla Cedros (see Figure 1). Small outlying populations grow at lower elevations on volcanic mesas, bedrock slopes, and along washes. Extensive open stands grow on the Vizcaíno Peninsula. Several species extend into Baja California Sur as understory to Mexican oak woodlands. Botanical collections show that species composition is conspecific with chaparral in California and northern Baja California, but additional congeners from the Mexican mainland occur in chaparral from the Sierra San Francisco to the cape. See tables 3 and 5 for ranges of chaparral and pine-oak woodland species.

3.1. Sierra La Asamblea

Chaparral grows mostly on north-facing slopes >1,200 m of Cerro San Luis and granitic bedrock slopes of a plateau 7 km to the south (see Figure 2a). Contiguous chaparral dominated by *Adenostoma fasciculatum* covers the north-facing slope of Cerro San Luis (see Figure 3a). Other species recorded in botanical collections and in photographs by K. Geraghty (pers. comm.) are *Ceanothus greggii* var. *perplexans*, *Arctostaphylos glauca*, *A. peninsularis*, *Cercocarpus betuloides*, *Garrya grisea*, *Rhus ovata*, *Quercus turbinella*, *Q. cedroscensis*, *Q. ajoensis*, *Rhamnus insula*, *Heteromeles arbutifolia*, and *Juniperus californica*. *Pinus monophylla* woodlands cover steep north-facing exposures. The plateau (1,200 to 1,400 m) is covered with open chaparral in association with scattered *Brahea armata* (Minnich *et al.* 2011a). Collections in the upper Arroyo Las Palmas drainage on the west side of the plateau record *Arctostaphylos peninsularis*, *Rhus ovata*, *Rhamnus insula*, *Prunus ilicifolia*, *Heteromeles arbutifolia*, *Quercus turbinella*, *Q. cedroscensis*, *Q. peninsularis*, *Garrya veatchii*, and *Adenostoma fasciculatum*. *Xylococcus bicolor* was reported in the range by Wiggins (1980). Sparse woodlands of *Quercus peninsularis* grow across the range, but most remarkable are stands of *Q. chrysolepis* in association with *Pinus monophylla* and *Brahea armata* on several resistant granite bedrock slopes of the plateau (see Figure 3b). North-facing slopes in the southeastern plateau are covered with *Pinus monophylla* woodland in association with *Quercus turbinella*, *Q. peninsularis*, *Rhus ovata*, and *Arctostaphylos peninsularis*. The plateau is the southern limit of *P. monophylla* (Critchfield and Little 1966).

3.2. Sierra La Libertad

Chaparral occurs for 60 km along the crest of the Sierra La Libertad (see Figure 2b), and on summits detached from the main sierra in the northwest (28.84ºN, 113.71ºW) and on Cerro La Sandia (1,772 m). Extensive open chaparral on granitic substrate in the north forms locally closed stands on the north-facing slopes of Cerro La Libertad, Cerro La Borreguera, and a summit near the San Juan mine. Although reported in botanical collections, *Adenostoma fasciculatum* is not as conspicuous as in the Sierra La Asamblea. Chaparral species recorded in the range include *Ceanothus greggii* var. *perplexans*, *Arctostaphylos glauca*, *A. peninsularis*, *Rhus ovata*, *Cercocarpus betuloides*, *Heteromeles arbutifolia*, *Rhamnus insula*, *Quercus cedroscensis*, *Q. turbinella*, *Garrya veatchii*, *Garrya grisea*, *Prunus ilicifolia*, and *Juniperus californica*. Intervening granite plateaus on the crest are covered with open chaparral, *Juniperus californica*, and rare colonies of *Q. peninsularis*. *Rhus kearneyi*, *Xylococcus bicolor*, and *Malosma laurina* grow at lower elevations, often along arroyos.

South of the Cerro San Juan mine, granites are capped by extensive porous basalts with little chaparral, especially on caprock plateaus and south-facing slopes. Open stands grow on steep north-facing slopes and talus to the highest summit on the range (1,640 m), the shrubs frequently arranged in elongated, parallel linear strips at the base of basalt cliffs, at contacts between lava flows, and along bedrock fractures. The association of these southern stands with *Brahea armata* (Minnich *et al.* 2011a) suggests that chaparral is colonizing bedrock seeps. Botanical collections have not been taken in the volcanic caprock part of the Sierra La Libertad. Chaparral on Cerro La Sandía is restricted to talus and consists of *Garrya grisea*, *Quercus turbinella*, and *Rhus kearneyi*. *Malosma laurina* and *Xylococcus bicolor* grow in nearby washes.

3.3. Sierra San Francisco

Open chaparral occurs on north-facing slopes of the highest summit (Cerro "1590"), just south of the village of San Francisco, and several nearby summits in association with woodlands dominated by *Quercus oblongifolia*, a mainland Mexican species that is closely related to *Q. engelmannii* of northwest Baja California and southern California (see Figure 2c; Felger *et al.* 2001, eFloras 2008). Local chaparral patches grow on north-facing slopes of nearby summits, and *Q. oblongifolia* woodlands descend major canyons and arroyos with near-surface water in association with *Brahea armata* (Minnich *et al.* 2011a). A botanical collection by Tucker (SDNHM 95184) discusses the mixture of "intermediate oaks in the Sierra San Francisco." A *Quercus ajoensis-turbinella* intermediate was also reported (SDNHM 59827). Dominant chaparral species include *Xylococcus bicolor*, *Rhus kearneyi*, *Prunus ilicifolia*, *Rhamnus insula*, and *Heteromeles arbutifolia*. *Malosma laurina* grows along arroyos (Rhode 2002).

3.4. Volcán Las Tres Vírgenes

Dense chaparral grows > 1,500 m on the north-facing slope of the primary volcano, with open stands descending to 1,350 m (see Figure 2d). Botanical collections reveal that upper slopes have *Ceanothus greggii* var. *perplexans*, *Ceanothus oliganthus*, *Garrya grisea*, and *Rhus kearneyi*. Collections below 1,500 m include *Xylococcus bicolor*, *Rhamnus insula*, *Rhus ovata*, and *Quercus ajoensis*. Open chaparral covers the north-facing slope of the northern volcano.

3.5. Isla Cedros

The crest of Isla Cedros has two narrow belts of chaparral at elevations > 300–600 m, one extending from North Point to Cerro "1063", and the other along the north facing slope of Cerro Redondo (see Figure 2e). In the fog zone <600 m are dense *Pinus radiata* forests, with chaparral understory, forming narrow ribbons of solid forest *ca.* 300 m wide, mostly along the primary ridgeline. One stand extends 4.3 km southward from North Point and the other for 6.2 km along an isthmus between Cerro "1063" and Cerro Redondo. Pine stands are flagged by winds from the west and north at right angles to local topography, due to persistent strong winds and fog drip that sustains these closed-cone forests. Stands are mostly open, but gradually increase in cover with elevation above the pine belt. Contiguous stands grow on steep north facing slopes of Cerro "1063", and on Cerro Redondo. Species in the northern pine forest include *Rhus integrifolia*, *R. lentii*, *Malosma laurina*, *Ceanothus verrucosus*, *Heteromeles arbutifolia*, *Xylococcus bicolor*, *Juniperus californica*, *Rhamnus crocea*, and *Quercus cedroscensus*. Shrubs recorded on north-facing slopes of the southern summit include *Quercus cedroscensus*, *Garrya veatchii*, and *Xylococcus bicolor*. *Rhus lentii* and *Juniperus californica* were collected on the south face Cerro Redondo.

3.6. Chaparral outliers

Small patches of open chaparral grow in many localities below the primary sierras, but few botanists have collected them (see Figure 1). The north-coastal chaparral belt at Ensenada extends southward to the foothills of the Sierra San Pedro Mártir (Minnich and Franco-Vizcaíno 1998) and Mesas San Carlos and Santa Catarina, south of El Rosario. In the nearby coast range, small colonies grow on summits 8 km W of El Progreso, and along a ridge (800–1,050 m) *ca.* 14 km NE of Santa Catarina Sur. Local populations continue south along arroyos within 5 km of the beach from Punta Baja to Punta Canoas to locally near Bahia Blanco and Punta Prieta, where collections document *Rhus integrifolia* and *Malosma laurina*. On the Vizcaíno Peninsula, extensive stands of *Rhus lentii*, a close relative of *R. integrifolia*, occur with *M. laurina* in the hills and alluvial plains near Punta Eugenia and Bahía San Cristobal. This area is subject to frequent fog and low clouds, similar to nearby Isla Cedros, but appears to lack the chaparral diversity of the island.

Farther inland, many small populations occur between the southern limit of chaparral in Sierra San Pedro Mártir near Cerro Matomí and the Sierra La Asamblea. In the far northern Central Desert are stands growing in talus of basalt caprock on the north flank of Mesa El Mármol (1,070 m) and on a mesa 5 km to the east (29.94°, 114.70°), as well as on a granite bedrock slope beneath a volcanic mesa at 29.89°, 114.73°. Chaparral occurs intermittently for 6 km along the northern exposures of an 1,100-1,200 m high ridge near Arroyo Zamora. Nearby Cerro La Aguatosa (1,345 m) contains open stands consisting of *Rhus ovata*, *Juniperus californica*, *Quercus turbinella* and *Prunus ilicifolia*. Granite bedrock slopes at Cataviña have scattered patches that include *Juniperus californica* (Wells 2000). The north-facing slopes of a nearby basalt mesa (1,000 m) have *Rhus ovata* and *Juniperus californica*, as well as the chaparral leaf succulent *Yucca whipplei* (29.72°, 114.59°). Several chaparral patches grow on granite bedrock >800 m at 29.67°, 114.52°. Cerro El Pedregoso, an eroded cinder cone with summit elevations of 1400 m, is covered with open stands of *Juniperus californica*, *Rhus ovata*, *Quercus turbinella*, and *Rhamnus insula*. Farther south, chaparral grows on granite bedrock (900 m) just west of a basalt mesa (1,100 m, 29.57°, 114.63°), at Mesa El Gato where *Rhamnus insula* was collected, and on a granite bedrock surface within lava flow/cinder cone terrain in the upper headwaters of Arroyo El Gato.

South of Laguna Chapala, open chaparral occurs on granitic bedrock slopes > 600 m in a coastal range south of Mesa El Salado. To the east are sparse chaparral stands on granite bedrock slopes, and a volcanic mesa 5 km S of the Sierra La Asamblea. Chaparral grows on the coastal foothills of the Sierra La Libertad west of Mesas Catarina and Corral Blanco, again on granite bedrock slopes > 600 m. A few colonies were found at 1000 m on a resistant granite bedrock exposure southeast of the Sierra La Libertad. Collections of *Malosma laurina* and *Xylococcus bicolor* have been recorded from Cerro San Juan in the northern Sierra San Francisco near Misión Santa Gertrudis. The total area of outlying chaparral populations totals 27,956 ha, mostly *Rhus lentii* stands on the Vizcaíno Peninsula.

3.7. Sierra La Giganta and the Cape Region

Chaparral stands are not clearly evident on Google Earth imagery of the Sierra La Giganta. Botanical collections in the mountains south of San Ignacio document several shrub species growing in Mexican-oak woodlands on the crest of the Sierra La Giganta, and along streams below in the thorn-scrub belt (see Figure 4a). The northern Sierra La Giganta (also known as Sierra San Pedro or Sierra Guadalupe), has widespread *Quercus oblongifolia* and *Q. ajoensis* woodland > 1200 m with understory of *Prunus ilicifolia*, *Xylococcus bicolor*, *Heteromeles arbutifolia*, and *Malosma laurina* (cf. De la Cueva *et al.* 2010). The nearby Sierra Agua Verde has scattered *Q. oblongifolia* woodlands with *H. arbutifolia*, *M. laurina* and *Rhus kearneyi*. Isolated oak woodlands grow on north-facing bedrock cliffs, talus, and canyon floors above 1000 m at several summits near 26.66°, 112.14°. Botanical collections record *Prunus ilicifolia*, *Malosma laurina*, and *Garrya silicifolia* along Arroyo El Horno near Cerro Loreto which hosts an isolated woodland of *Q. tuberculata*, the northernmost outpost of this oak on the Baja California Peninsula (see Figure 4b). Rare *Q. tuberculata* woodland also occurs on an unnamed summit at the headwaters of Arroyo El Encinal, and on several summits 25 km south of Loreto (1,375 m, see Figure 4c).

Botanical collections record rare coastal populations of *Malosma laurina* on washes from the Vizcaíno Peninsula to the cape region and *Rhus kearneyi* in desert drainages from the Sierra La Libertad to the Sierra La Giganta (see Figure 1). In the Cape Region, Mexican oak woodland dominated by *Quercus tuberculata* grows > 1,000 m on a few summits of the Sierra Las Cruces (1,243 m), east of La Paz, but chaparral has not been collected there (see Figure 4d). A few colonies grow 15 km south on the crest of Sierra El Novillo. In the Sierra La Laguna (2,067 m, see Figure 4e), *Q. tuberculata* woodland is extensive > 1000 m before giving place to

Q. devia woodland > 1300 m. *Pinus cembroides* (Mexican pinyon pine) is abundant > 1,500 m (*e.g.*, Arriaga *et al.* 1994, Díaz *et al.* 2000, Arriaga and Mercado 2004). *Arbutus peninsularis* and *Q. rugosa* grow near watercourses. Botanical collections record chaparral along watercourses and as understory in pine-oak forest, including *Malosma laurina*, *Prunus ilicifolia*, *Heteromeles arbutifolia*, as well as the congeneric shrubs *Prunus serotina* and *Garrya salicifolia* which occur on the Mexican mainland.

4. PACKRAT MIDDENS, CLIMATE CHANGE, AND CHAPARRAL "SKY ISLANDS"

The biogeography of chaparral sky islands of the desert Baja California Peninsula is a legacy of plant migrations associated with climate change since the Last Glacial Maximum (LGM). Vegetation maps and botanical records presented in this study provide new insight on fossil floras of packrat middens. Plant macrofossil records represent one of the few direct proxy evidences for terrestrial (non-marine) environments. Evidences of climate change have been bolstered by the emergence of studies that infer environmental change from new data sources including high-resolution stable-isotope records from marine sediment cores (Gibbard and Van Kolfscholten 2004) that resolve orbital- and millennial-scale climate oscillation cycles (Dansgaard *et al.* 1993, Broecker *et al.* 1985, Alley and Clark 1999, Zachos *et al.* 2002, Rahmstorf 2002, Alley *et al.* 2003), as well as from global climate models (*e.g.*, COHMAP 1984; and for the Pacific coast, Bartlein *et al.* 1998).

4.1. Fossil floras in LGM–Early Holocene packrat middens

Four Late Pleistocene and Early Holocene packrat midden sites (17.5–10 ka) in the Central Desert and the Sierra San Pedro Mártir record chaparral in areas that now host full-desert vegetation. The dominant species in this region at present include *Larrea tridentada*, *Yucca valida*, *Fouquieria columnaris*, *F. diguetii*, *Pachycormus discolor*, *Machaerocereus gummosus*, *Agave deserti*, *Ambrosia chenopodifolia*, *Atriplex magdalenae*, *Atriplex polycarpa*, *Ambrosia bryantii*, *Lycium* spp., *Encelia farinosa*, *Opuntia* spp., *Ferocactus* spp., and *Jatropha cuneata* (Wiggins 1980, Rhode 2002). This is comparable to Late Holocene midden plants and arthropod fauna recorded near Cataviña (1.8 ka; Clark and Sankey 1999, Sankey *et al.* 2001).

Packrat middens show two trends in Late Glacial chaparral biogeography: lower altitudinal zonation, and species extensions to lower latitudes. A full Glacial midden NW of Santa Inés dated at 17.5 ka was found at 550 m elevation in granite bedrock terrain that characterizes the Cataviña region (Wells 2000). This midden recorded *Pinus quadrifolia, Juniperus californica, Adenostoma fasciculatum, Quercus turbinella,* *Prunus lyonii*, and *Eriodictyon angustifolium*. Based on midden abundances, the dominant species are *Pinus quadrifolia* and *Juniperus californica*, followed by *Adenostoma fasciculatum* and *Quercus turbinella*. Another midden found by Wells (2000) in a rock shelter at 594 m in volcanic rock NW of Misión San Fernando at lat. 30°, dates to the Pleistocene–Holocene transition at 10-10.2 ka. Species recorded in the midden are *Juniperus californica, Adenostoma fasciculatum, Quercus turbinella, Prunus lyonii,* and *Arctostaphylos glandulosa*. Based on abundances, the dominant species was *Juniperus californica*, followed by *Adenostoma fasciculatum* and *Quercus turbinella*. This area presently has sparse chaparral cover of *Xylococcus bicolor* and few *Juniperus californica*. A third midden, found at the base of a 3-m high basalt outcrop in the western Sierra San Francisco at 780 m (Rhode 2002), *ca.* 300 km south of Cataviña, was dated to Late-Pleistocene, possibly Younger Dryas, with a carbon date of 10.2 ka calibrating to 12.4–11.5 ka. This midden recorded *Juniperus californica*, *Arctostaphylos peninsularis*, and *Malosma laurina*. No desert shrubs were recorded in these middens. Thirty-eight middens at three localities at 650–900 m on the eastern escarpment of the Sierra San Pedro Mártir show vegetation change spanning the past 33 ka (Holmgren *et al.* 2011). They found pinyon woodland 300–500 m below modern stands mapped in Minnich and Franco-Vizcaíno (1998), and Minnich *et al.* (2000). Full Glacial midden species are all found at nearby higher elevations including *Pinus monophylla* (*californarium*), *Juniperus californica*, *Arctostaphylos* spp., *Cercocarpus betuloides*, *Quercus chrysolepis*, *Q. Cornelius-mulleri* (*turbinella-john-tuckeri*) and *Rhus* spp. Desert taxa replaced pinyon woodlands beginning 14 ka.

4.2. Evidence of Late Pleistocene moist climate in surface hydrology and Glaciation

Until recently, midden biota was used as a primary source of evidence in the reconstruction of past environments. The occurrence of chaparral at lower elevations and lower latitudes in the Late-Pleistocene is supported by geomorphic evidences of greater landscape surface water in northern Baja California and the southwestern USA that is broadly consistent with stable isotope records of GRIPP /Vostok ice cores and marine cores (Rahmstorf 2002). These records show that moist LGM climates persisted globally until *ca.* 14 ka, with another episode at 12.5–11.5 ka (Younger Dryas). Moist climates also persisted in central Baja California during the Milankovitch solar maximum of the Early Holocene to *ca.* 7 ka. Laguna San Felipe ("Laguna del Diablo") was a pluvial lake beginning at 34.0 ka. Planktonic saline-water diatoms were present from 34 to 28 ka and lacustrine conditions persisted until 12.0 ka, but the lake bed may have been dry in the Younger Dryas (11.0 to 10.0 ka; Ortega-Guerrero *et al.* 1999). In the Mojave Desert of southern California, high stands supported by runoff from the Owens, Amargosa and Mojave Rivers occurred between 31 and 18 ka, with high persistent lakes from 26 to 16 ka. Most lakes had another high stand at *ca.* 12 ka (Benson *et al.* 1990, Enzel *et al.* 2003, Wells *et al.* 2003, Anderson and Wells 2003). Lake Elsinore, in coastal southern California, was an overflowing lake during the LGM from 19.2 to 17.2 ka, followed by drying through the Late Glacial/ Holocene transition to 9.4 ka (Kirby 2005).

In the Sierra Nevada, cosmogenic dating of moraines in the Tioga series at Bishop Creek indicate that glaciers extended to the base of the mountains from 28 to 17 ka, then retreated abruptly to the crest of the range at 15.0–14.5 ka, followed by the minor Recess Peak advance at 13.5 ka (Gillespie and Zehfuss 2004, Phillips *et al.* 2009). Moraines on Mt. San Gorgonio in the San Bernardino Mountains of southern California, the southernmost mountain glaciation in the USA, recorded advances at 20 and 16 ka, and recessional moraines at the base of cirque headwalls at 12.5 ka (Owen *et al.* 2003). Moist climates along the Pacific coast of California and Baja California are attributed to the southward displacement of the polar jet stream, but is this the case in Baja California below lat. 30ºN? We looked at this question from the standpoint of midden studies that use climate analogies, the cistern effect of midden habitats, chaparral species, and global paleocirculation.

4.3. Midden paleo-vegetation and "climate analogues"

Paleo-vegetation and climate interpretations from early packrat midden studies are based on a "vegetation analogy" model that points to locations where vegetation strongly resembles the fossil-species composition of the midden. Differences in climate between the midden and the analogue target are assumed to represent climate change since the midden date. Wells (2000) proposes an analogy between midden vegetation at San Fernando and Santa Inés to the west face of the Sierra San Pedro Mártir where *Pinus quadrifolia* grows in chaparral dominated by *Adenostoma fasciculatum*, *Quercus turbinella* and *Juniperus californica* between 1100 and 2100 m. Wells (2000) recognizes that pinyon pine, junipers and chaparral occur at lower latitudes at Cerro San Luis (Sierra La Asamblea), Sierra La Libertad and Volcán Las Tres Vírgenes. It was deduced that chaparral islands in the Central Desert represent remnants of former continuous distributions due to contagious expansion of *P. monophylla* and associated chaparral from the Sierra San Pedro Mártir.

The analogue for the Sierra San Francisco midden proposed by Rhode (2002) is the "'soft' chaparral from Ensenada to San Diego". He concludes that the contents of the Sierra San Francisco midden extend the record of juniper and other chaparral taxa *ca.* 400 km further south of their present distributions in southern California and northern Baja California. Based on where *Juniperus californica* grows today in the mountains of southern California, it was inferred that the Late Glacial climate in the Sierra San Francisco was mediterranean, with an average annual precipitation of 25 cm, compared to present-day values of 10–15 cm, and with a larger component of winter precipitation. Based on a comparison with southern California, mean annual temperature was 15°C, and average temperatures were 5–6°C colder in winter and 1–2°C colder in summer.

The interpretation of climate change from paleobotanical evidence is confounded by circularity, because plants and climate are not treated independently. The vegetation analogy method also relies on the now discredited Clementsian notion that species assemblages move in consort (Clements 1916). The LGM-Holocene vegetation history in the western USA, as seen in high-resolution taxonomic records from packrat middens, clearly shows that individual species each have independent histories of migration and distribution, thus resulting in temporally loose, changeable vegetation assemblages (Van Devender 1990, Davis and Shaw 2001). In addition, the most geographically widespread species adapt to broad environmental diversity through genetic variability and physiological plasticity of populations, limiting the precision of inferences with regard to paleoclimate. Hence, without spatial baselines of paleo-vegetation, a site-specific choice of analogue vegetation amounts to space-for-time substitution. This incorporates no baseline except the specific species assembly of the midden, which is difficult to generalize spatially or temporally.

But in a larger sense, why choose analogous vegetation near San Diego, as opposed to a nearby place in Baja California much closer to the midden site? The analogue vegetation for the San Fernando and Santa Inés middens is in the Sierra San Pedro Mártir, where chaparral grows in areas with mean precipitation of 40-50 cm (Minnich *et al.* 2000). But similar chaparral vegetation exists today, with far less precipitation, above 1200 m in the nearby Sierras La Asamblea and La Libertad (see Table 2). *Pinus quadrifolia* presently grows only 30 km upstream from the San Fernando site, compared to 130 km away at the Sierra San Pedro Mártir. Moreover, the possibility of long-distance vicariant dispersal was not considered, even though pinyon nuts and some chaparral fruits are dispersed and cached over great distances by corvids and other birds (Vander-Wall and Balda 1977). Both contagious expansion and vicariant dispersal operate simultaneously, and long-distance dispersal was doubtless made more effective by reduced distance between chaparral islands associated with the downward displacement of *P. quadrifolia* and chaparral species in the past.

The existence of "sky islands" is not necessarily evidence of continuous distributions in the past. Using current evidence, it is not possible to test whether Central Desert chaparral is a consequence of vicariant dispersal or of contagious expansion and retreat. Moreover, the premise of former continuous distributions does not account for the ecological differences among these pinyons. In northwest Baja California, *P. quadrifolia* grows in dense chaparral on the west slope of the peninsular ranges, while *P. monophylla* grows with desert chaparral on the arid eastern escarpments (Minnich and Franco-Vizcaíno 1998, Minnich *et al.* 2011b). And many chaparral species extend farther south than the San Fernando/Santa Inés midden sites, with *Adenostoma fasciculatum* extending to the Sierra La Libertad, and *Quercus turbinella* to Volcán Las Tres Vírgenes. *Malosma laurina* in the Sierra San Francisco midden, which Rhode (2002) calls a characteristic coastal sage scrub plant, grows throughout the Peninsula to the cape region.

Rather, we propose that the biogeography of chaparral sky islands fundamentally represents the balance between plant migration and selection (Sauer 1988); in this case the southward expansion of chaparral during the LGM, and the selective elimination of chaparral during the Holocene. The most impressive range extensions in the Pleistocene were *Pinus quadrifolia* and *Arctostaphylos glandulosa* from the Sierra San Pedro Mártir (Minnich and Franco-Vizcaíno 1998) to Cataviña and San Fernando, and *A. peninsularis* from the Sierra La Libertad to the Sierra San Francisco. These range extensions of 50 to 100 km also demonstrate the areas of post-Glacial extinctions of these species.

Perhaps the most important findings in midden records are that chaparral grew 500 m lower than the present limits, and the relative impoverishment of chaparral midden materials at the Sierra San Francisco compared to middens at San Fernando and Santa Inés. The latter trend suggests decreasing chaparral abundance and diversity then, as now.

4.4. Habitat bias of rock shelters

All four midden sites were discovered in resistant granite or volcanic bedrock surfaces that act as cisterns. These sites host abnormally moist vegetation that can root into bedrock fractures and thus rely on bedrock runoff from surrounding impermeable rock surfaces. Impervious surfaces also retard evaporation from the regolith. In volcanics, water percolating through porous rock layers can produce springs at the contact with underlying impermeable basement. The midden sites at San Fernando and Sierra San Francisco lie at the base of basalt cliffs. Basalt exposures of the Sierra La Libertad currently exhibit bands of chaparral along contacts, including the lowest stands at the base of basalt outcrops. The Santa Inés site occurs in granite bedrock slopes with local sediment-filled depressions likely kept moist by runoff from surrounding impermeable rock surfaces.

An example of a moist-cistern habitat is a *Quercus chrysolepis* population growing on the rubble of a resistant pluton in the Sierra La Asamblea (see Figure 3b), which is 175 km from the nearest stand in the Sierra San Pedro Mártir. That habitats in the Cataviña-Santa Inés-Misión Santa Maria region are unusually moist is best evidenced by the occurrence of thousands of dwarf upland populations of blue fan palm (*Brahea armata*) (Minnich *et al.* 2011a). The distribution of the dwarf phenotype is limited to widespread granitic bedrock units in parts of the Sierras La Asamblea and La Libertad, and at three other granite exposures to the north, near the Sierras San Pedro Mártir and Juárez. Chaparral outlier populations frequently occur on granitic bedrock slopes.

The occurrence of fossil middens on bedrock slopes is a generic problem because rock-sheltered sites are necessary for the preservation of paleo-middens from weather. The assessment of vegetation and climate change at midden sites may be appropriate for the specific site if the approach accounts for the presence of abnormally mesic species that rely on bedrock runoff. The regional extrapolation of midden materials in the vegetation analogy method, across many geologic`substrates, may lead to conclusions that favor anomalously large changes in vegetation and climate, because bedrock sites are likely abnormally moist (see *e.g.* Salama *et al.* 1994, Singhal and Gupta 1999, Murty and Raghavan 2002, Kosugi *et al.* 2006). Whether midden habitats in granitic or volcanic bedrock may have represented the model distribution of extensive paleo-chaparral, or alternatively, of isolated patches in a milieu of xeric vegetation, cannot be assessed from currently available evidence.

5. MODERN "SKY ISLAND" CHAPARRAL DIVERSITY AND CLIMATE CHANGE

Botanical and map distribution data of chaparral sky islands show large differences in species diversity and life trait properties from north to south despite small climate gradients (see Table 3). At present, mean winter temperatures differ by 5.0°C

TABLE 3. Species composition of chaparral "sky islands" in the Central Desert, and as understory of pine-oak woodland in Baja California Sur (north to south), determined by consulting databases of botanical collections at the San Diego Natural History Museum (SDNHM), the University of California Riverside (herbarium.ucr.edu), the Flora of North America (http://www.efloras.org), and Wiggins (1980). Obligate seeders: Ag, *Arctostaphylos glauca*; Cg, *Ceanothus greggii* var. *perplexans*; Cv, *Ceanothus verrucosus*; Non-obligate seeders: Af, *Adenostoma fasciculatum*; Ap, *Arctostaphylos peninsularis*; Co, *Ceanothus oliganthus*; *Arctostaphylos peninsularis*, Ap. Sprouters: Cb, *Cercocarpus betuloides*; Fc, *Fremontodendron californicum*; Gg, *Garrya grisea*; Gv, *Garrya veatchii*; Gs, *Garrya salicifolia*; Ha, *Heteromeles arbutifolia*; Ml, *Malosma laurina*; Pi, *Prunus ilicifolia* (*lyonii*); Rc/i *Rhamnus crocea* (*insula*); Ri, *Rhus integrifolia*; Rl, *Rhus lentii*; Rk, *Rhus kearneyi*; Ro, *Rhus ovata*; Qc, *Quercus cedroscensus*; Qt, *Quercus turbinella*; Xy, *Xylococcus bicolor*. Nonsprouting conifer: Jc, *Juniperus californica*.

TABLE 3

	Seeders			Sprouters																			
Region	**Af**	**Ap**	**Ag**	**Cg**	**Cv**	**Co**	**Fc**	**Cb**	**Gg**	**Gv**	**Gs**	**Ha**	**Ml**	**Pi**	**Rc/i**	**Ri**	**Rl**	**Rk**	**Ro**	**Qc**	**Qt**	**Xb**	**Jc**
C.Potrero/ Cataviña														x					x		x		x
S. La Asamblea	x	x	x	x			x	x	x	x		x		x	x				x	x	x	x	x
S. La Libertad	x	x	x	x				x	x	x		x	x	x	x			x	x	x	x	x	x
Cerro San Juan													x									x	
S. San Francisco									x			x	x	x	x			x				x	
Las Tres Vírgenes				x		x			x				x		x			x	x		x	x	
Cedros Island					x					x		x	x		x	x	x			x		x	x
Pacific coast of Central Desert													x			x							
Punta Eugenia													x			x	x						
S.La Giganta N (S. San Pedro)												x	x	x				x				x	
S. La Giganta (Loreto)											x		x	x				x					
S. La Giganta (Gulf coast)													x										
S. La Laguna											x	x	x	x									

TABLE 4. Diversity of chaparral species by life traits.

Location	Obligate Seeder	Sprouter/Seeder	Sprouter	Total
Sierra La Asamblea	2	4	9	16
Sierra La Libertad	2	3	11	16
Sierra San Francisco	0	0	7	7
Volcán Las Tres Vírgenes	1	1	7	9
Isla Cedros	0	1	8	9
Sierra La Giganta				
San Pedro	0	0	5	5
Cerro Loreto	0	0	4	4
Coast	0	0	1	1
Cape (Sierra La Laguna)	0	0	4	4

and mean summer temperatures by only 1.0°C across the Central Desert. Mean annual precipitation is uniformly 10–15 cm at stations on the desert floor, although the proportion of summer precipitation (July–September) increases from *ca.* 17% in the north to 46% at San Ignacio (see Table 2). Global climate models suggest that latitudinal precipitation gradients were stronger in the Central Desert (Bartlein *et al.* 1998) because the closer year-round proximity of the jet stream both increases winter precipitation in the north, and decreases monsoon precipitation in the south. Hence, species differences between sky islands may represent Late Glacial selection pressures contributing to chaparral migrations and modern distribution patterns.

The higher summits of the Sierras La Asamblea and La Libertad are covered with dense stands of floristically rich chaparral that rival those in mediterranean northern Baja California and California. These populations comprise both obligate "seeders" (non-sprouters if defoliated by fire) in the genera *Ceanothus* and *Arctostaphylos*, and nonobligate seeders in *Adenostoma*; as well as sprouting, fleshy-fruited shrubs in *Garrya*, *Quercus*, *Heteromeles*, *Rhamnus*, *Prunus*, *Rhus*, *Malosma*, *Cercocarpus*, and *Xylococcus* which are characterized by long-range seed dispersal through animal transport of fleshy fruits, as well as wind-dispersed seed (*Cercocarpus*) (see Table 4). In contrast, the Sierra San Francisco, Volcán Las Tres Vírgenes, and Isla Cedros all have floristically poor, open chaparral dominated by "sprouters" in *Garrya*, *Quercus*, *Heteromeles*, *Prunus*, *Malosma*, and *Rhus*. The seeding species *Ceanothus greggii* var. *perplexans* and *C. oliganthus* are restricted to the upper catchments of Volcán Las Tres Vírgenes, and *C. verrucosus* to the fog zone of Isla Cedros. Even fewer chaparral species, entirely fleshy-fruited sprouters, grow sparingly at lower elevations of the Central Desert, especially on granite bedrock surfaces and talus slopes below basalt caprock mesas. The same resprouting species also occur farther south in Mexican pine-oak woodland and in arroyos in the Sierra La Giganta and the cape region. Some shrubs, such as *Malosma laurina* and *Rhus kearneyi*, transcend the entire Peninsula (see Table 3).

These patterns represent a continuation of the same trends in species composition that occur in southern California. Near Los Angeles, California Vegetation Type Maps (VTM) show that chaparral has an abundance of obligate seeders including *Ceanothus megacarpus* in coastal ranges, *C. crassifolius* in the Transverse Ranges and *C. greggii* var. *perplexans* in the peninsular ranges (Weislander 1938). At lower elevations near Los Angeles and farther south, the chaparral in San Diego County and northern Baja California southward to the Sierra San Pedro Mártir is dominated by non-obligate seeders (resprouters and seeders) such as *Adenostoma fasciculatum* and *A. sparsifolium*. Semiarid "petron" chaparral growing along the arid leeward slopes of the southern California mountains and the Sierras Juárez and San Pedro Mártir, with mean annual precipitation comparable to the Central Desert sky islands, is dominated by sprouting species *Quercus turbinella*, *Q. Cornelius-mulleri*, *Cercocarpus betuloides*, *Prunus ilicifolia*, *Rhamnus ilicifolia*, and *Rhus ovata*.

We propose that in the Central Desert, moist Glacial climates selected for seeding chaparral species, due to high productivity and fuel-accumulation rates, and consequent burning. The drier climate of the Holocene selectively eliminated seeders, with sprouters persisting in wet sites, even to the lowest elevations, through efficient dispersal and colonization. Chaparral "seeding" species are characterized by punctuated mass establishment of seedlings from refractory seed immediately after fires. Impermeable and indigestible refractory seed not only links germination to disturbance, but also discourages long-distance dispersal by birds and mammals. However, locally dispersed seed banks result in mass recruitment and species dominance that overwhelms fleshy-fruited sprouters. In the north, "seeders" may still benefit from high rates of burning due to higher winter rainfall and productivity. Seeders may also benefit from widespread water-retaining granitic substrate, as opposed to the porous volcanics that dominate the Sierra San Francisco and fresh lava flows of Volcán Las Tres Vírgenes. In the south, limited productivity lengthens fire intervals, which selects against seed banking, but fleshy-fruited sprouters reproduce continuously at low rates and are dispersed by birds and other animals. Sprouters adapt to large climate variability by efficient vicariant seed dispersal and recolonization of suitable habitat.

5.1. Climate of the Central Desert and Global Paleo-Circulation

It is useful to establish the equatorward limit of moist Pacific coast LGM climate from first principles of atmospheric physics, which may help to constrain conclusions of past chaparral elevational zonation and latitude limits in the central Peninsula. Here we examine atmospheric lapse rates, the role of the coastal marine layer, and limits of the jet stream precipitation based on the conservation of momentum and vorticity of global atmospheric circulation.

5.2. Atmospheric lapse rates

Past elevational limits of chaparral can be estimated from the atmospheric lapse rate; that is, the decrease in temperature with altitude. In the Central Desert, the current lower limit of chaparral is virtually isotropic, ranging from 1,200 m in the Sierra La Asamblea to 1,350 m at Volcán Las Tres Vírgenes. Packrat middens document a downward zonation of chaparral by 500 m. The atmospheric lapse rate is globally uniform at *ca.* 6.5°C 1,000 m^{-1} (International Civil Aviation Organization 2010); this is clearly seen in climatological data for the mountains of southern California and northern Baja California (Minnich 2001, 2007). During peak evapotranspiration (ET) in summer, ambient temperatures at 850 mbar (*ca.* 1500 m) range from 23–25°C and are isotropic through northern Baja California and southern California (National Climatic Data Center 2010).

Because mean lapse rates represent the integration of marine and continental evapotranspiration, subcloud adiabatic mixing, and latent heat-flux warming aloft from condensation and precipitation (Barry and Carleton 2001), we assume that the lapse rate was the same in full Glacial climates as at present. Hence, temperature departures since the Last Glacial Maximum were broadly dependent on departures in sea-surface temperature in the tropical oceans of that time. Stable-isotope records of marine and ice-sheet environments give temperature decreases of 3°C in tropical seas during the LGM (Rahmstorf 2002). This departure is consistent with glacier mass-balance modeling and geomorphic evidences from tropical glaciers (Hostetler and Clark 2000, Kaser and Osmaston 2002). Since air-mass thermal structure is isothermal at constant pressure (≈ altitude) in the tropics, temperature departures in the Peninsula since the Glacial Maximum were likely also *ca.* 3°C cooler than at present. Using the standard lapse rate, we can infer that eustatic sea-level lowering from the build-up of ice sheets increased the elevation of local mountains ~100 m, producing an additional local cooling of *ca.* 0.6°C. Thus, based strictly on temperature and evapotranspiration, a 3–4°C cooling of the local troposphere would lower the 25°C isotherm *ca.* 500–700 m, consistent with the elevation departure of chaparral packrat middens.

5.3. The coastal marine layer and Isla Cedros

Chaparral on Isla Cedros, and also in the coastal regions of northern Baja California, grows to as low as 300 m, nearly 1000 m below the present limits of chaparral in the Central Desert. This disparity is a result of the cool, moist Pacific marine layer, a steady-state feature that forms from the cooling and moistening of the tropospheric boundary layer overlying the cold, upwelling California Current. Sea-surface temperatures at the latitude of the Central Desert average *ca.* 20ºC. The marine layer, which is associated with extensive coastal low clouds (stratus), is capped by a strong thermal inversion that separates it from warm and dry subsiding air masses aloft.

In the present climate, the marine layer fluctuates from 300 to 800 m depth in summer, restricting its influence to the immediate coast. We suggest that a strong summer jet stream produced by the Laurentide ice sheet in the LGM, as modeled in global climate models (*e.g.*, Bartlein *et al.* 1998), would produce a climatological increase in the depth of the marine layer, and more extensive penetration of cool, moist air and reduced ET in the central desert interior than at present. Given fixed standard lapse rates, a deep full Glacial marine layer (*ca.* 20ºC at sea level and with mean depth > 1,000 m) would have produced larger negative temperature departures, from the coast to the base of the mountains, than from global cooling alone.

We hypothesize that during Glacial Maximum, summer climates in the Central Desert were comparable to deep marine-layer conditions usually seen in April and May in the present climate. Strong negative-temperature departures would expand chaparral habitat nearly to sea level and inland to the sierras, as suggested by Pleistocene packrat midden records. A modern analogy occurs at the latitude of the Sierra San Pedro Mártir, where chaparral gives place to coastal sage scrub below 1000 m, but coastal sage scrub turns to chaparral near the coast at Colonet and Eréndira. Marine layer climate may help to explain the presence of the Catalina Cherry trees (*Prunus lyonii*) of the southern California Channel Islands in the San Fernando and Santa Inés middens (Wells 2000).

5.4. Southern limit of jet stream precipitation in full Glacial Baja California

Global lake-stand data indicate that mediterranean-climate regions along the southern margin of the Northern Hemisphere polar-front jet stream experienced heavier precipitation during the LGM than at present (Street and Grove 1979, Vaks *et al.* 2006). This is consistent with global climate models, which show a southward dislocation of the jet stream from present climate (COHMAP 1984, Bartlein *et al.* 1998). A critical question is whether the southward displacement of the jet stream by the Laurentide ice sheet would have brought greater precipitation to the Central Desert. Rainfall along the Pacific coast is almost exclusively linked to mechanical atmospheric lift of stable air from positive vorticity advection in cold frontal disturbances ahead of troughs in the jet stream. In a classical study of extratropical cyclones in California, Elliot (1958) documented the deepening of the marine layer that merges with upper cloud layers before the passage of cold fronts, giving rise to extensive cloud shields and long periods of steady precipitation.

The climatological dislocation of the jet stream has an equatorward limit based on conservation of angular momentum and absolute vorticity. Frictional loss of atmospheric angular momentum in tropical easterly flow is transferred as frictional gain in westerly flow at high latitudes, thus resulting in a net global exchange of angular momentum (mv = 0). To conserve momentum, equatorward expansion of the westerlies would require the strengthening of tropical easterlies, in effect constraining the equatorward extent of the westerlies (Palmén and Newton 1969, Barry and Carleton 2001). The jet stream also has a theoretical limit near latitude 30°N due to the conservation of absolute vorticity, which is supported by data on the latitudinal atmospheric profiles of geostrophic zonal winds. To conserve absolute vorticity, atmospheric cyclonic curvature and shear in troughs increases equatorward, due to the decreasing vorticity contribution of the coriolis force (Barry and Carleton 2001). For the jet stream to reach the equator would require that the contribution of curvature and shear to vorticity approaches infinity. The limit varies with Rossby wave number, and ranges from 35°N (high Rossby wave number) in zonal (west-east) atmospheric flow, to 30°N (low Rossby number) in meridional (north-south) flow.

These conservation principles assert that *the equatorward limit of the jet stream at 30° must be retained regardless of climate state*, modern or Glacial. Hence, for storms passing through the Central Desert at the LGM, a potential increase in precipitation in Baja California would have been inhibited by the region's equatorward position to the jet stream. The resulting negative vorticity advection and atmospheric subsidence would detach the marine layer from upper cloud layers in the frontal zone, thus virtually precluding precipitation. The marine layer would then move anticyclonically in northeast flow, away from the Peninsula, as part of the trade wind layer of the subtropical North Pacific Ocean. Similarly, the equatorward limit of reliable jet stream precipitation in the Mediterranean climate of Chile is also at 30° latitude (Direccción Meteorológica de Chile 2010), even though the southern hemisphere jet stream is stronger under the current ice-sheet climate, than in the northern hemisphere.

We hypothesize that increases in precipitation in the Central Desert during Glacial times were small and latitude dependent, with cooler temperatures and reduced ET largely contributing to moister climates and interior lakes. Laguna San Felipe (~lat. 31°) was closer to the jet stream and likely received increased frontal precipitation and runoff from orographic precipitation on the Sierra San Pedro Mártir, but not at levels of the Mojave Desert (Enzel *et al.* 2003), as evidenced by the lack of shorelines that would indicate deep lakes. Large precipitation changes are unlikely at Laguna Chapala (lat. 29.4°), which now forms shallow lakes, even with modest precipitation variability. The playa lies in a volcanic field of extensive basalt flows and hardpan soils that are conducive to flash flooding. The sensitivity of Laguna Chapala to variability in full Glacial climate is made uncertain by its low sill level. Although the western playa receiving runoff from Laguna Chapala has a sill level of 15 m above the lake bed, shorelines indicative of deep lakes are again not evident on Google Earth, nor at other playas in the volcanic field. As suggested by packrat midden records, Late Pleistocene chaparral extended south of present distributions, but this trend is phased with minimal increase in precipitation. Chaparral expansion was instead encouraged by reduced temperature and evapotranspiration, bolstered by more robust marine layer penetration onto the Peninsula. These trends are supported by a stronger summer jet stream in an ice sheet climate, as predicted by global climate models. An analogy of LGM summer climate would be present-day climate in May and June before the jet stream retreats to Canada.

5.5. Climate and vegetation in the Early Holocene solar maximum

The LGM was followed by the Milankovitch solar maximum, the warmest phase of the Holocene with more extensive global monsoons than present, including the North American monsoon (*e.g.*, Poore *et al.* 2005). Moist climate, sediment-accumulating lakes, and widespread chaparral persisted in the Central Desert into the Early Holocene (Metcalfe 2006), at a time when pluvial lakes had desiccated or disappeared in the Great Basin (Street and Grove 1979). Laguna Chapala accumulated lacustrine sediments from 10.0 to until 7.45 ka (Davis 2003), while Laguna San Felipe was a small lake until 7.0 ka (Ortega Guerrero *et al.* 1999). Early Holocene lakes have been attributed to increasing winter precipitation, in part due to catastrophic drainage of Lake Agassiz into the North Atlantic, which would produce stronger westerlies and more upwelling (Van Devender 1990, Davis 2003). However, the relatively small water volume of ice-sheet lake discharges should have had only ephemeral influence on sea-surface temperatures in the Atlantic, as compared with ice-sheet purges (Heinrich events) (MacAyeal 1993, Alley and MacAyeal 1994). Van Devender (1990) proposed an increase in Early Holocene winter rainfall and cool-summer vegetation in Baja California, due to strengthening of the California current and upwelling. Colder seas during a period of warming atmosphere, however, would produce stronger temperature inversions and diminish precipitation (cf. Ingram 1998). This is supported by pollen data that indicate drier-than-present climate in the Oregon Cascades (Long *et al.* 1998), and results from global climate models that show the jet stream moving northward with the retreating ice sheets from the LGM to the Early Holocene (COHMAP 1984, Bartlein *et al.* 1998). Only a poleward shift of the jet stream is consistent with both drier climate in Oregon (Long *et al.* 1998) and wet climate in Baja California. Studies of the Mid-Holocene in California provide evidences of dry climate. For example, submerged pine stumps dated from 6.3 to 4.8 ka (cal) reveal that Lake Tahoe was below sill heights (Lindstrom 1990), and glaciers may have been entirely absent in the Sierra Nevada during much of the Holocene (Clark and Gillespie 1997, Phillips *et al.* 2009).

Simulation of the North American monsoon by Bartlein *et al.* (1998) shows that Milankovitch forcing would result in increasing sensible and convective heating over the southwest USA deserts, and monsoon precipitation along the Baja California Peninsula. An enhanced summer monsoon is parsimonious with earlier lake disappearances northward from Baja California (7.0–7.45 ka) to Arizona and California (8–7–9.0 ka), and the Great Basin (10.0 ka) because monsoon moisture is progressively depleted northward from the Gulf. At the same time, high lake stands may arise from singular flood-producing events of a single season (Enzel *et al.* 1992). For example, lacustrine conditions in the region could be produced by a slight increase in the frequency of tropical cyclones.

We conclude that Late Pleistocene chaparral survived into the warmer Early Holocene by responding to increased summer rain of the North American monsoon linked to the Milankovitch solar maximum (Metcalfe 2006). This view is consistent with the northward retreat of the jet stream as simulated in global climate models, and high monsoon lakes in Old-World deserts in association with the Milankovitch solar maximum (Street and Grove 1979, COHMAP 1984).

5.6. Vegetation lag time and phenological plasticity

Fossil midden records at San Fernando (Wells 2000) and Sierra San Francisco (Rhode 2002) at the warmer Late Pleistocene-Holocene transition may have a legacy of plant distributions lagging behind climatic fluctuations, even at scales of millennia. In long-lived communities such as chaparral, extirpation to desert vegetation may require centuries or even millennial-scale climate change (cf. Thompson 1988, 1990, Nowak *et al.* 1994). The vegetation-lag hypothesis is not trivial, considering recent discoveries of chronic, abrupt century-to-millennial scale climate change in association with Dansgaard-Oeschger cycles and Heinrich events in full Glacial climates (*e.g.*, reviews in Rahmstorf 2002, Alley *et al.* 2003, Seidov and Maslin 1999, 2001, Schmittner *et al.* 2002). The combination of migrational lags and millennial-scale climate changes may produce only gradual, buffered plant migrations against climate fluctuations.

The Early Holocene persistence of California chaparral may be related to the capacity of evergreen shrubs to be phenologically plastic to precipitation at any season. Plasticity is adaptive because of the advantage conferred by flexibility in the initiation and duration of growth, in response to an unpredictable environment. For example, an August tropical cyclone in southern California (5 cm precipitation) was followed by chaparral growth, flowering and fruiting (Minnich 1985). Most chaparral congeners live in summer-rain climates in Arizona, central and southern Baja California, and mainland Mexico. Flowering data from herbarium collections show growth flushes in spring in California; but flushes occur in spring and early fall in Arizona and central Baja California, and fall in Mexico, the late-season flush being a consequence of summer rain. Moreover, the geographic range of chaparral from winter-rain climates in California to summer-rain climates in Mexico suggest that sclerophylly is a generalized adaptation to drought, regardless of season (Minnich 1985, Barbour and Minnich 1990, Valiente-Banuet *et al.* 1998). Midden records suggest that chaparral persisted into summer-rain climates during the Milankovitch solar maximum. Phenotypic plasticity with climate change may explain the disjunct distributions—west and east of the Gulf of California—of the closely related or possibly conspecific *Quercus peninsularis* versus *Q. emoryi*, and *Q. engelmannii* versus *Q. oblongifolia*.

5.7. "Missing" chaparral in Baja California Sur

Wells (2000) points to an "isolating barrier" to chaparral at San Ignacio in the mid-Peninsula, noting that only a few sprouting chaparral species occur in the nearby Sierra La Giganta, only 50 km south, despite summit elevations of 1,600 m. He speculates that "pinyon pines and chaparral" never migrated past Volcán Las Tres Vírgenes during the LGM. The composition of oak woodlands also shifts from California to mainland Mexico species with decreasing latitude (see Table 5). The Sierra La Asamblea hosts conspecifics to the Sierra San Pedro Mártir including *Quercus chrysolepis* and *Q. peninsularis*. Only *Q. peninsularis* grows in Sierra La Libertad, while *Q. oblongifolia* and *Q. ajoensis*—both widespread in NW Mexico, Arizona and New Mexico (Felger 2001)—occur in the Sierra San Francisco and northern Sierra La Giganta (Sierra San Pedro). *Q. tuberculata*, another widespread drought-deciduous oak in northern Mexico, dominates oak woodlands on Cerro Loreto in the central Sierra La Giganta and pine-oak forest in the cape region in association with *Q. devia*.

TABLE 5. Distribution and species composition of pine-oak woodlands. Species: Qcr, *Quercus chrysolepis*; Qpn, *Quercus peninsularis*, Qob, *Quercus oblongifolia*; Qaj, *Quercus ajonensis*; Qtb, *Quercus tuberculata*; Qb, *Quercus brandegei*; Qdv, *Quercus devia*; Qru, *Quercus rugosa*; Apn, *Arbutus peninsularis*; Pm, *Pinus monophylla*; Pr, *Pinus radiata*; Pc, *Pinus cembroides* (*lagunae*).

	Woodland oaks and other species									**Conifers**		
Region/ species	**Qcr**	**Qpn**	**Qob**	**Qaj**	**Qtb**	**Qb**	**Qdv**	**Qru**	**Apn**	**Pm**	**Pr**	**Pc**
S. La Asamblea	x	x		x						x		
S. La Libertad		x										
S. San Francisco			x	x								
V. Las Tres Vírgenes				x								
Isla Cedros											x	
S. La Giganta N (S. Pedro/ Guadalupe)			x	x								
S. La Giganta S (C. Loreto)					x							
Cape (S. La Laguna)			x		x	x	x	x	x			x

Several factors appear to contribute to the disappearance of chaparral at 27.5°N. lat. The southward displacement of the summer jet stream to lower latitudes by the Laurentide ice sheet, predicted in global climate models of the LGM, is unlikely to increase winter precipitation at this latitude, and also diminishes warm-season monsoon precipitation (Bartlein *et al.* 1998). Hence, Late Glacial climate in the southern Peninsula may have been drier than present. We further suggest that the southern limit of chaparral, present and past, is also related to the position of the large Vizcaíno Peninsula, which turns the California current and the marine layer westward into the open Pacific, thus resulting in discontinuously warmer waters along the Pacific coast south of Punta Eugenia. While sea breezes bring cool northwest winds to the Peninsula as far south as the Sierra San Francisco, southwesterly winds bring warmer, more unstable Pacific air masses and higher orographic monsoon precipitation to the Sierra La Giganta and the cape ranges. The importance of the Vizcaíno Peninsula on modern climate is supported by present-day distribution of thorn scrub, which occurs locally as far north as the Sierra San Francisco but is widespread south of San Ignacio. Higher summer rain, under high ET, selects for shallow-rooted, summer active/drought-deciduous mesophyllous thorn scrub. In drought, thorn scrub persists near dormancy, thus placing this life strategy at an advantage over evergreen chaparral. Drought-deciduous trees may also compete against sun-demanding evergreen shrubs. The presence of chaparral along arroyos may be related to fluvial disturbances that denude thorn scrub, facilitating access to regolith water in the dry season, and thus encouraging chaparral recruitment. Chaparral also survives above the thorn-scrub belt on the highest peaks in drought-deciduous Mexican oak parklands. The Early Holocene Milankovitch solar maximum may have increased summer precipitation compared to present climate, and encouraged the expansion of thorn scrub and Mexican oak woodlands northward along the sierras of the southern Peninsula, but fossil evidence is not available.

6. CONCLUSIONS

The evaluation of chaparral biogeography since the LGM requires modern baseline data of its present distribution and species composition. We present the first detailed maps, interpreted from Google Earth imagery, of mediterranean chaparral and Mexican pine-oak woodland growing in the deserts of the Baja California Peninsula south of lat. 30°N. These vegetation maps can be refined in subsequent research. We show that chaparral is unexpectedly widespread in the Central Desert, occurring on the four highest sierras and on Isla Cedros. But small outlying populations also grow at lower elevations, especially on the Vizcaíno Peninsula, and on volcanic mesas, bedrock slopes, and along washes. Several species extend into Baja California Sur as understory to Mexican oak woodlands.

The interpretation of climate change from paleobotanical evidence in middens is confounded by circularity because plants and climate are not treated independently. Moreover, packrat middens are selectively preserved from weathering in abnormally moist bedrock habitats, in effect rock cisterns; thus broadscale interpretations from local middens may yield overestimations of climate change. The most important findings in Pleistocene midden records are that chaparral grew 500 m lower in elevation, and that several chaparral species had ranges 50 to 100 km further south than at present.

We suggest that changes in climate since the Last Glacial, especially of total precipitation, have been modest in the Baja California Peninsula. It is likely that moister climates resulted instead from cooler temperatures and reduced evapotranspiration. We propose that moist LGM climate selected for seeding—as opposed to sprouting—species of chaparral due to increasing productivity, fuel accumulation rates, and burning. Drier climate in the Holocene selectively eliminated seeders, with sprouters persisting in wet sites, even to the lowest elevations, through efficient dispersal and colonization. The "isolating barrier" to chaparral migration south of Volcán Las Tres Vírgenes may have been due to the seaward diversion of the upwelling California current by the Vizcaíno Peninsula, with corresponding increases in summer rain and thorn scrub vegetation. In the southern Peninsula, full Glacial climates may have been arid year-round.

Recent global warming is unlikely to have immediate effects on the chaparral sky islands of the Central Desert. The dynamics and migrations of long-lived chaparral species and oak woodlands lag behind climatic fluctuations, perhaps at scales of millennia. Moreover, evergreen shrubs are phenologically plastic to precipitation at any season, making them adaptive in an unpredictable environment, as evidenced by the distribution of many genera, both in the winter-rain mediterranean climate along the Pacific coast and in the summer-rain tropical climate of Mexico.

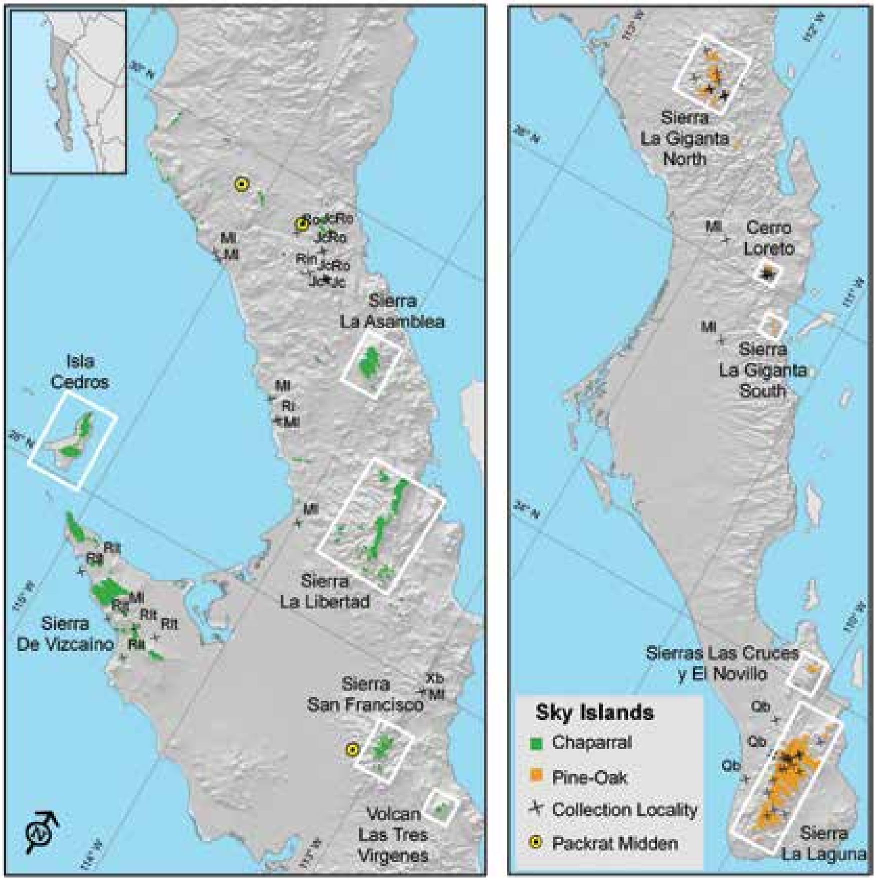

FIGURE 1. The distribution of chaparral and pine-oak "sky islands" in the central and southern Baja California Peninsula. For names of species see Tables 3 and 5.

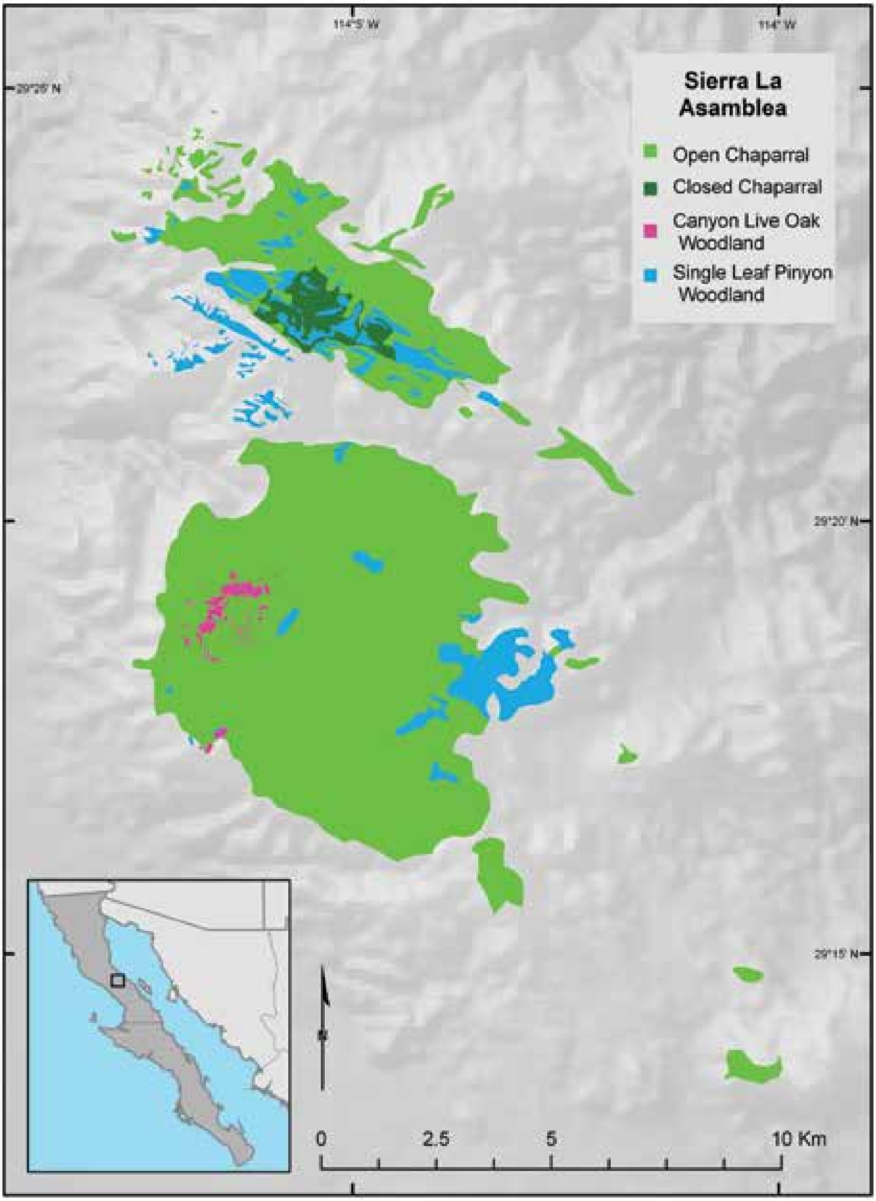

FIGURE 2. Detailed distribution of chaparral and oak woodlands in the Central Desert: (a) Sierra La Asamblea; (b) Sierra La Libertad; (c) Sierra San Francisco; (d) Volcán Las Tres Vírgenes; (e) Isla Cedros. FIGURE 2A (ABOVE)

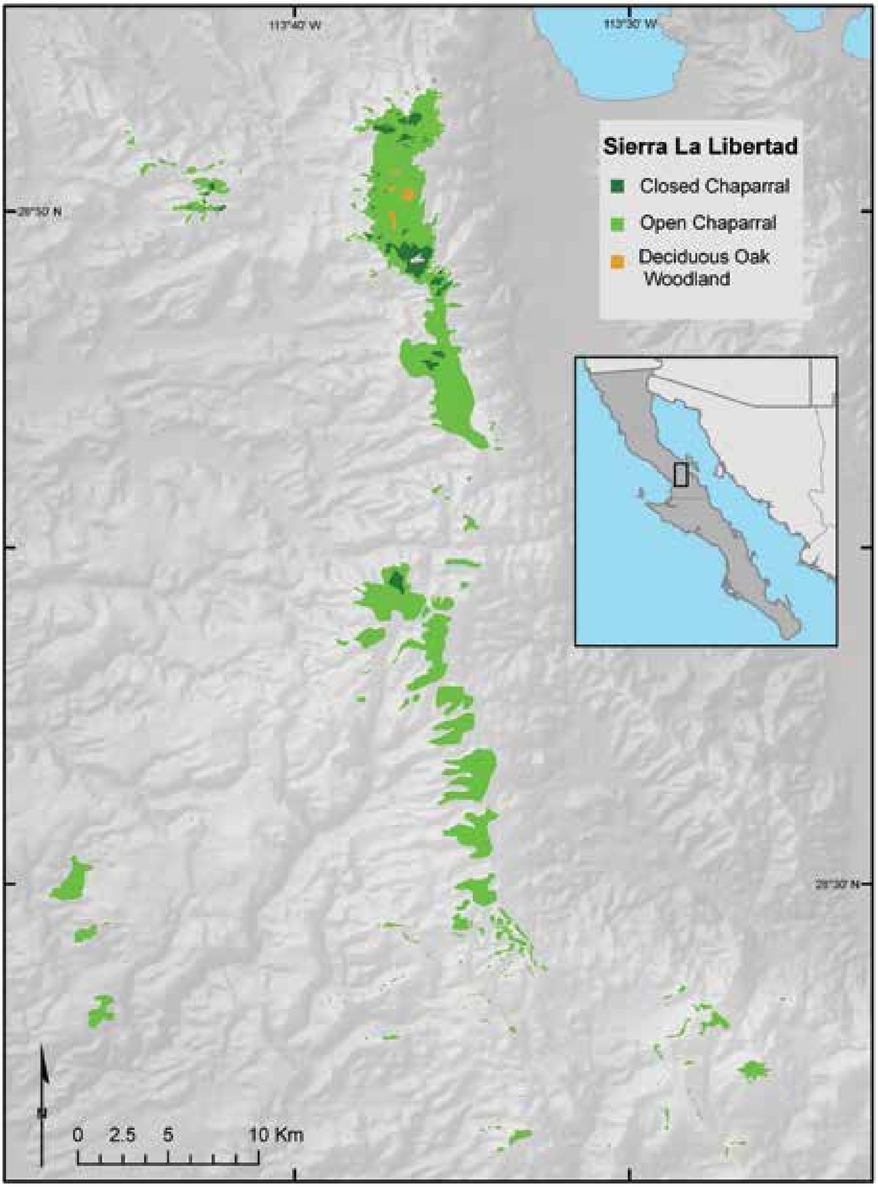
113°40' W
113°30' W
29°50' N
29°30' N
Sierra La Libertad
Closed Chaparral
Open Chaparral
Deciduous Oak Woodland
0 2.5 5 10 Km

FIGURE 2B.

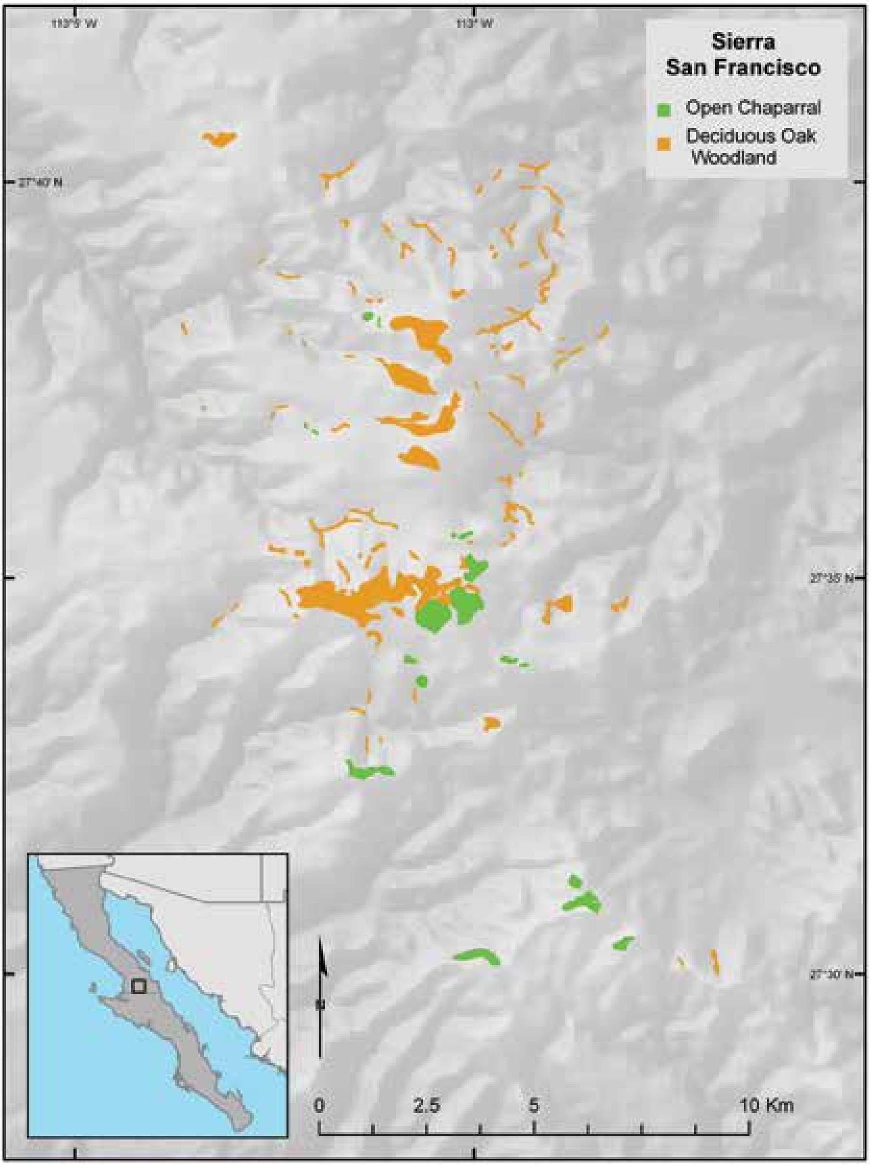
113°5' W
113° W
27°40' N
27°35' N
27°30' N
Sierra San Francisco
Open Chaparral
Deciduous Oak Woodland
N
0
2.5
5
10 Km

FIGURE 2C.

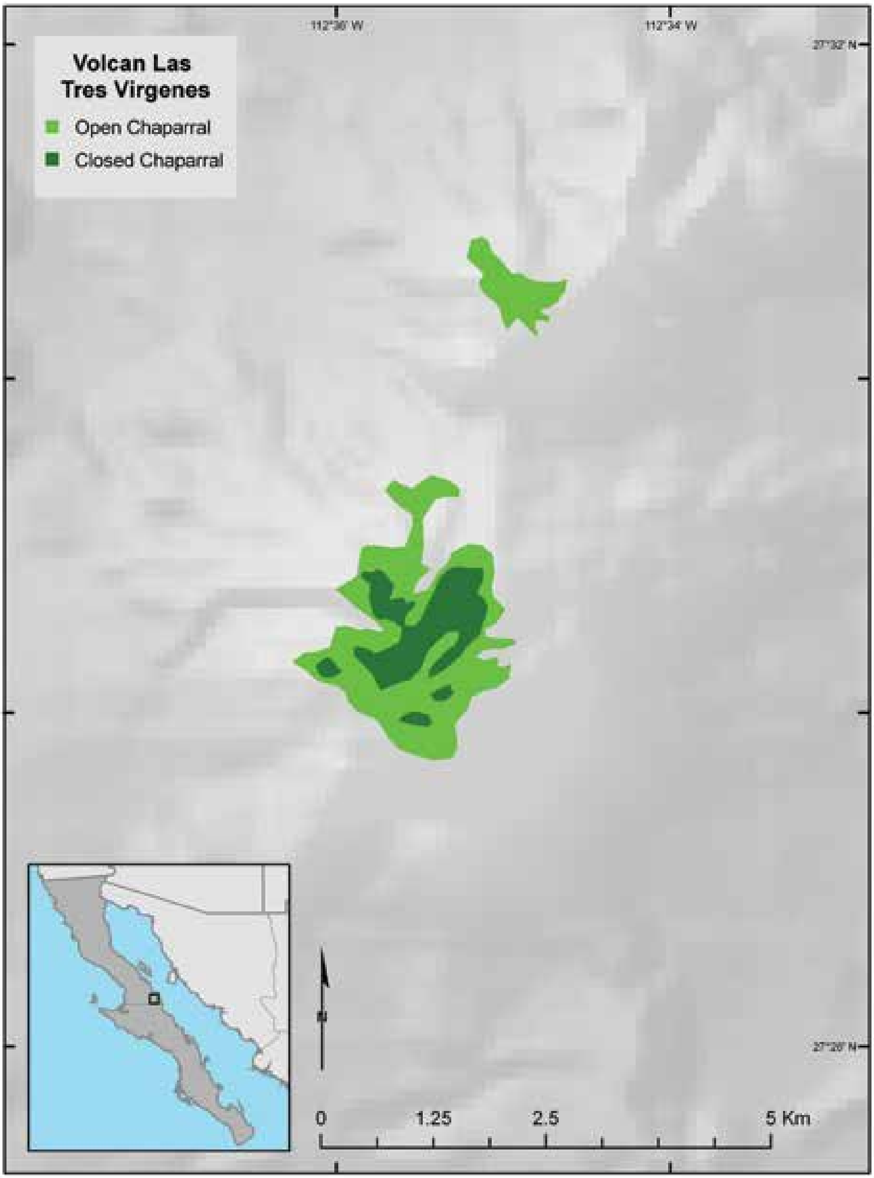
112°36' W
112°34' W
27°32' N
27°28' N
Volcan Las Tres Virgenes
🟩 Open Chaparral
🟩 Closed Chaparral
N
0
1.25
2.5
5 Km

FIGURE 2D.

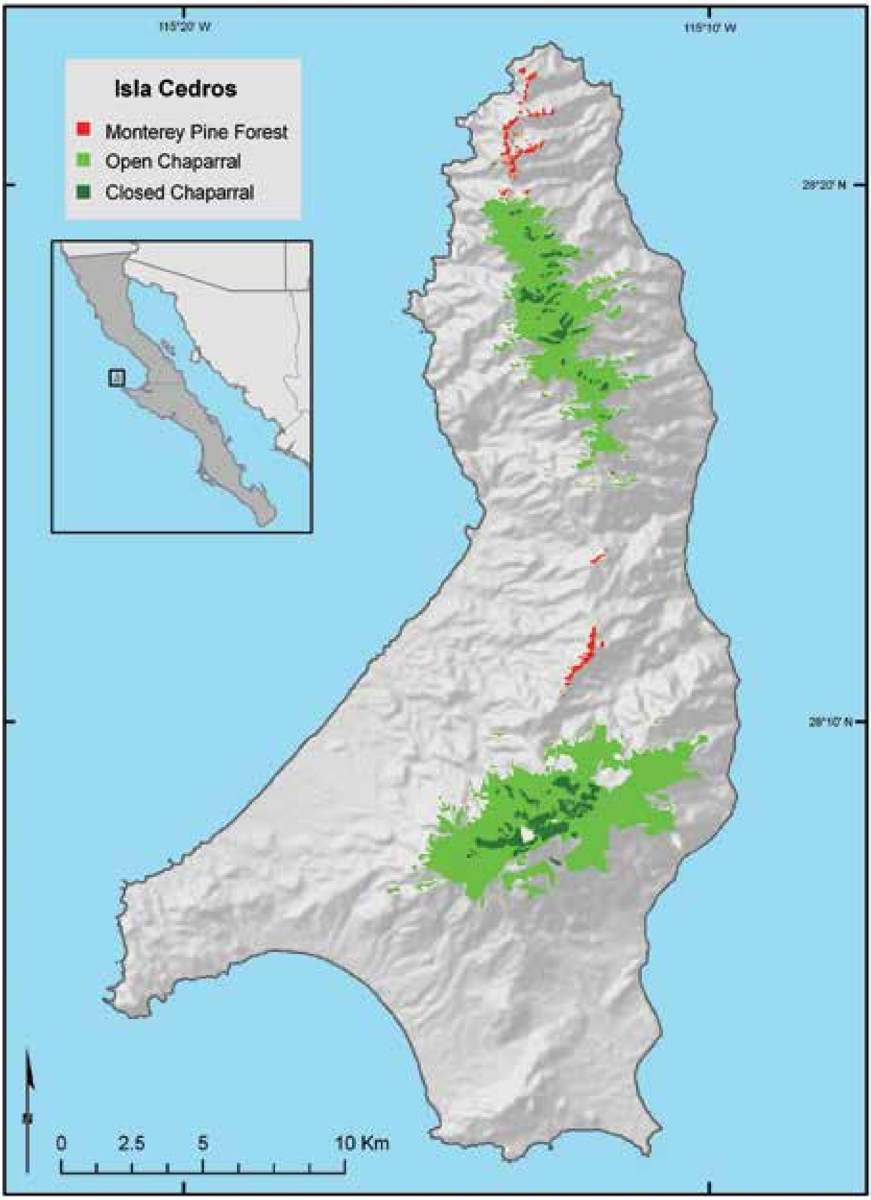
115°20' W
115°10' W
28°20' N
28°10' N
Isla Cedros
🟥 Monterey Pine Forest
🟩 Open Chaparral
🟩 Closed Chaparral
N
0
2.5
5
10 Km

FIGURE 2E.

FIGURE 3A (ABOVE). Chaparral on Cerro San Luis in the Sierra La Asamblea. *Adenostoma fasciculatum* (chamise) in the foreground growing with taller *Pinus monophylla*. The Gulf of California is in the distance (photo courtesy of K. Geraghty).

FIGURE 3B (BELOW). Resistant bedrock granite slope with *Quercus chrysolepis*, *Pinus monophylla*, and *Brahea armata* on the Sierra La Asamblea plateau (photo courtesy of K. Geraghty).

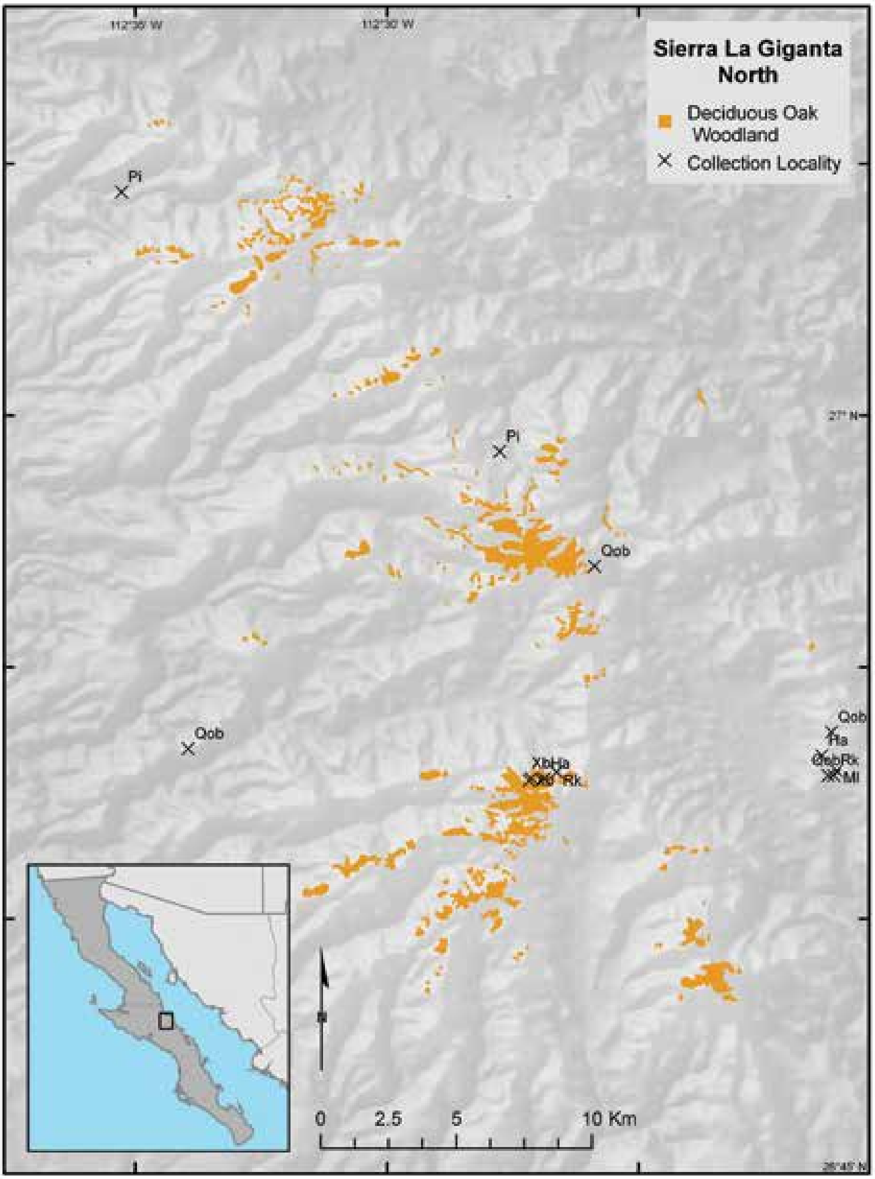

FIGURE 4. Detailed distribution of Mexican pine-oak woodlands in the Sierra La Giganta and the cape mountains: (a) Sierra La Giganta north (also known as Sierra San Pedro or Sierra Guadalupe); (b) Cerro Loreto; (c) Sierra La Giganta south; (d) Sierras Las Cruces and Novillo; (e) Sierra La Laguna. FIGURE 4A (ABOVE). For names of species see Tables 3 and 5.

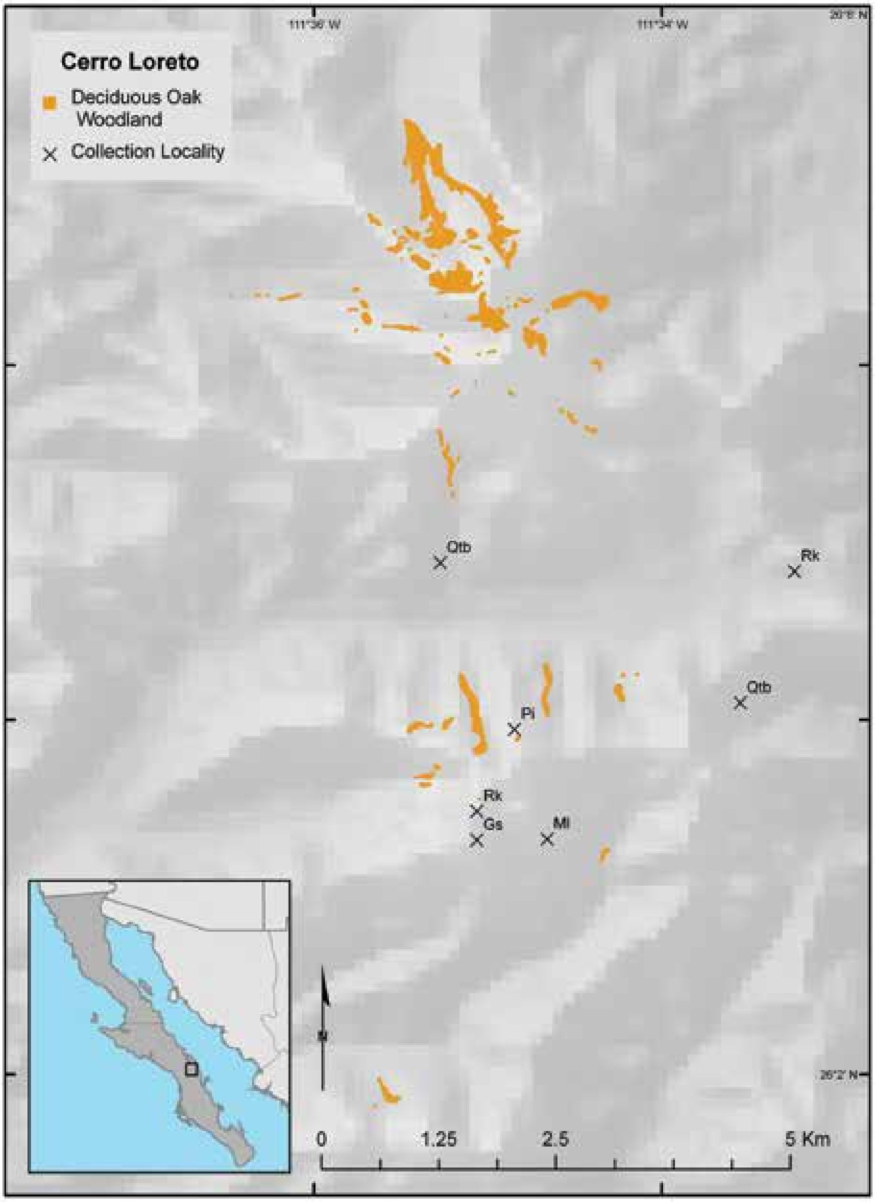

FIGURE 4B. For names of species see Tables 3 and 5.

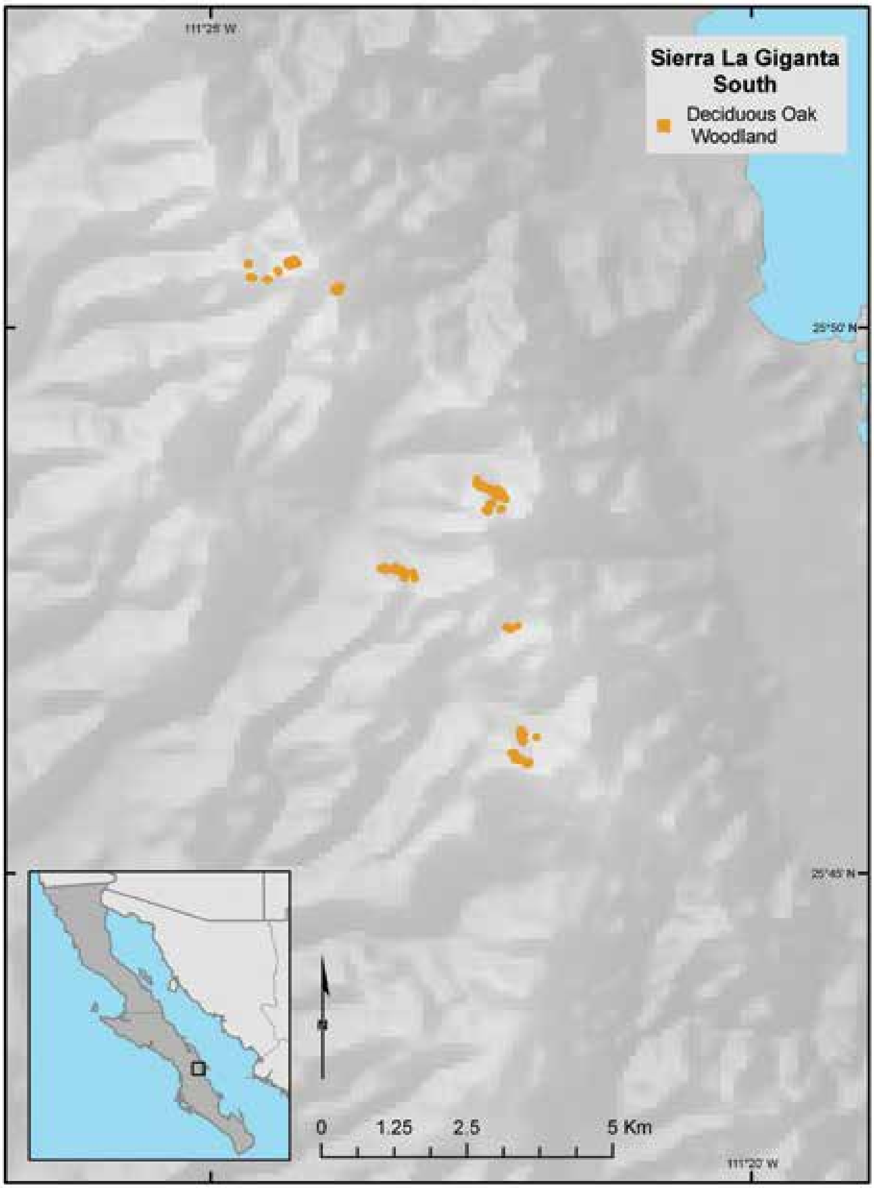
111°25' W
Sierra La Giganta South
Deciduous Oak Woodland
25°50' N
25°45' N
0
1.25
2.5
5 Km
111°20' W

FIGURE 4C.

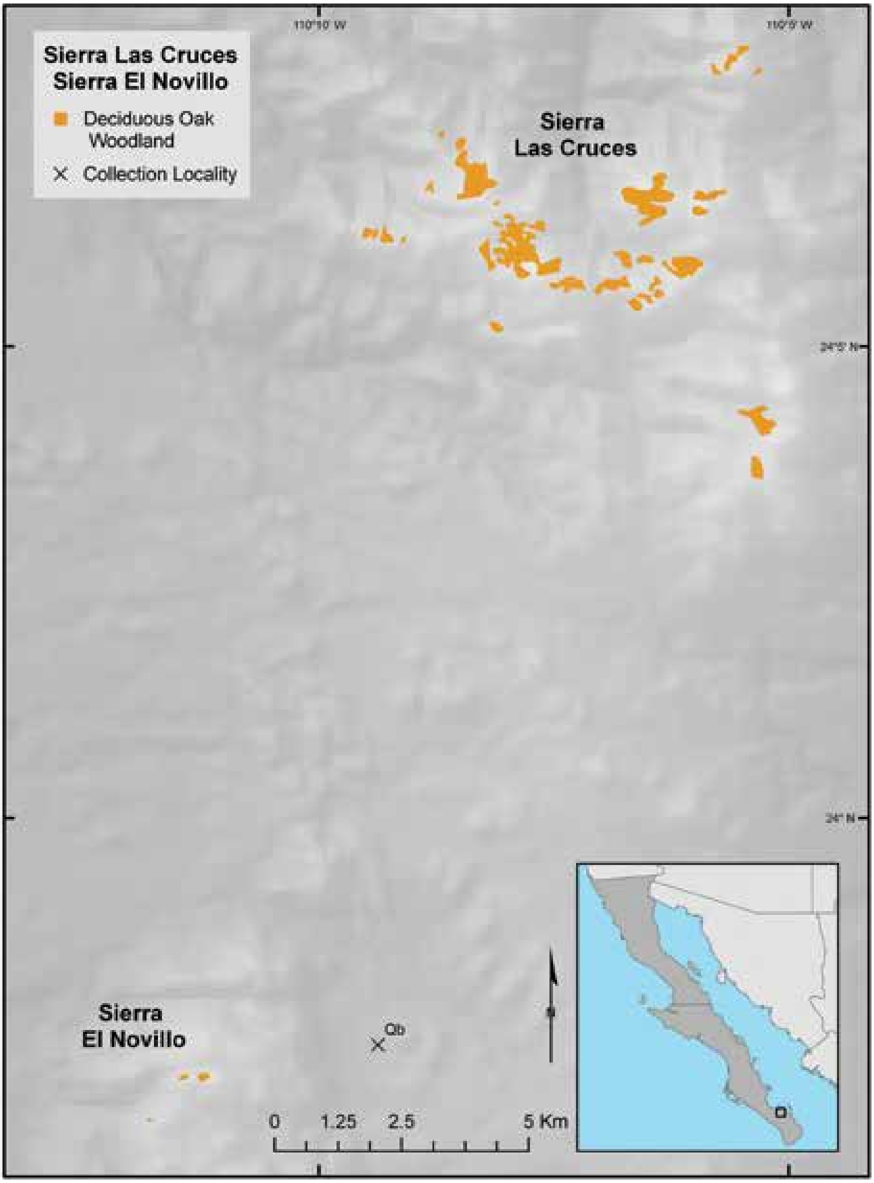
110°10' W
110°5' W
Sierra Las Cruces
Sierra El Novillo
Deciduous Oak Woodland
× Collection Locality
Sierra Las Cruces
24°5' N
24° N
Sierra El Novillo
Qb
0
1.25
2.5
5 Km

FIGURE 4D.

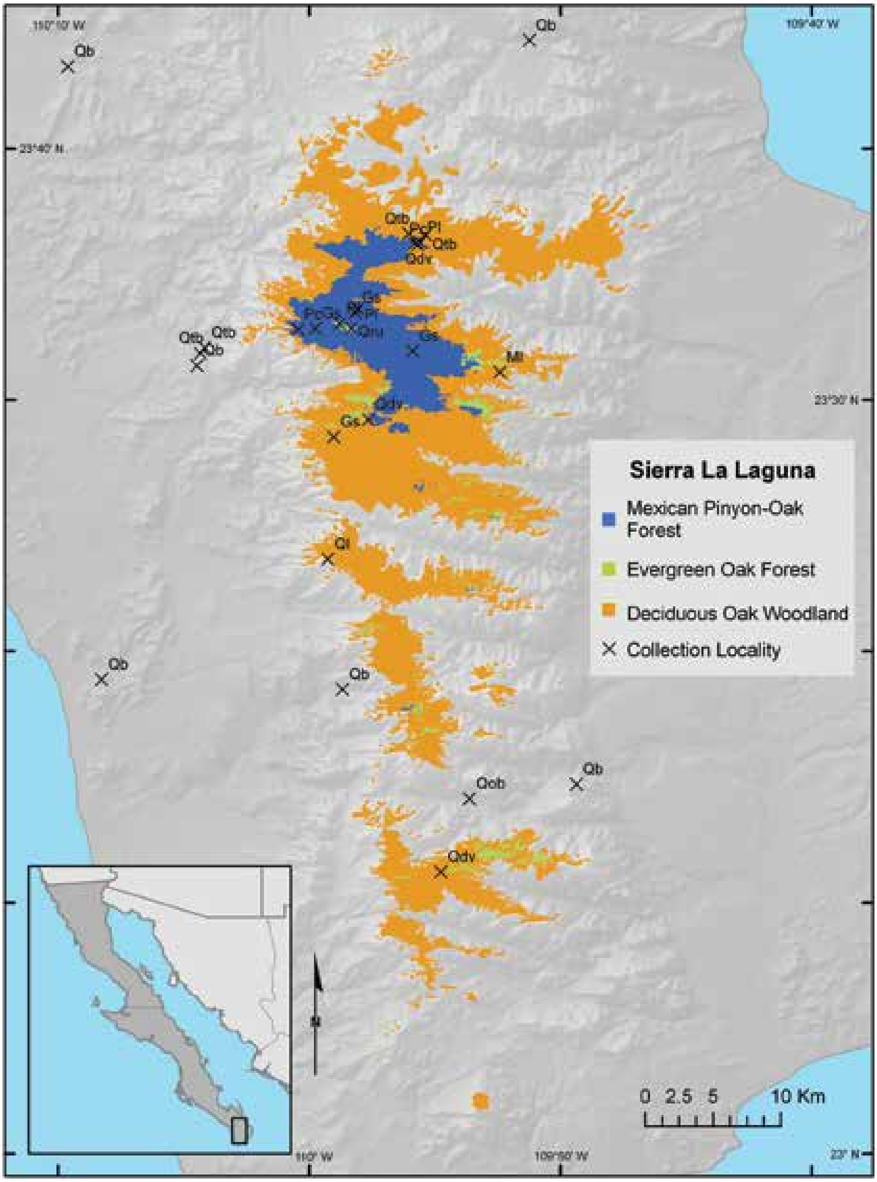

FIGURE 4E. For names of species see Tables 3 and 5.

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BAJA CALIFORNIA OASES: A HISTORICAL DESCRIPTION ABOUT THEIR LAND USE AND NATURAL RESOURCES

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Since the arrival of the Jesuits to the Baja California Peninsula in 1697, the historical process of colonization has produced important changes on the land use and the natural environment. The scarcity of water and rain pulses has been the most important limitation for Baja California colonization and has set the pace in desert ecosystem's land use. The oases, with springs or permanent water availability were the best places for the foundation of new missions, but the construction of reservoirs and channels for water management produced important transformations on the environment at this times. Subsistence agriculture; commercial crops like date palms, olives, sugar cane and livestock, have been the more important economic activities in the oases. Mainly in the south, people are still living in the missions founded by the Jesuits; however, in the last century, touristic activities have changed the use of natural resources in some oases. By using a collection of ground photograph taken at the beginning of the twentieth century and their repetition in 2008, the historical land use changes have being analyzed. A high demand on water resource because tourism and population growth have diminished agricultural activities. Nowadays, date and native palms occupied the agricultural landscape; and more trees and palms grow in the backyards of the houses. The biodiversity of Baja California inhabited oases is the result of more than three centuries of human activities and have been the drivers of the historical land use changes.

1. JESUIT PERIOD (1697–1768): THE FOUNDATION AND CONSTRUCTION OF THE ECOSYSTEM

1.1. Foundation

The scarcity of water, the harsh environment, and the difficulties to find appropriate locations for founding the missionary work was a common characteristic recounted in most of missionary documents (Kirchhoff 1942, Burrus 1966, León-Portilla 1990). These inconveniences were experienced in both peninsular territories, however compared with the northern region (still unexplored approximately until the 1746 exploratory trip by Fernando Consag), the southern parts of the Peninsula presents a more hospitable landscape, with springs of permanent surface water, where the first missions were established (Zavala-Abascal 1964, León-Portilla 1990, Minnich and Franco-Vizcaíno 1998, Lazcano-Sahagún 2000, Wehncke et al. 2009). Seventeen missions were founded in the southern part of Baja California during the Jesuitical period (1697–1768), however, although the better environmental conditions of the south, the missions founded in this region were never were completely self-sustaining. The organization of an economical support network by the Jesuit missioners was the corner stone for the maintenance of the missions in these hard conditions (Piñera-Ramírez 1991, Crosby 1994, Del Río 2003). The scarcity of water and the difficulty to obtain enough food by agricultural practices, forced the Jesuits to maintain a close relationship with the missions founded by them in the other side of the California Gulf. With the unique purpose of the evangelization, the missionaries were the only authority on the mission who took decisions on the land management. Once they found a good place, the church was constructed and the californios were attracted to live in the missions. The arrival of foreign people to live in Baja California Peninsula was always rejected by the Jesuit fathers. Inspired on the Tomas Moro utopia, they tried to construct a communal society where the feelings of brotherhood and mutual aid would not give capacity to the greed that the Spaniard civilians could bring to the missions. This fact delayed the establishment of the other kind of property and the development of other economic activities that were not agriculture and cattle ranch.

1.2. Construction: water and cultivable land

The construction of reservoirs and channels for water obtaining produced new environmental conditions on the oases that could have consequences on the biodiversity of the ecosystems. Sometimes water was available in the place where the mission was established, that was the case of Santa Rosalía de Mulegé, San Ignacio, La Purísima, and Santa Gertrudis, but in other missions water was brought from other places. The labor to obtain water was described by father Baegert showing us how hard it was to obtain water for the maintenance of the missions and the degree of transformations that the Jesuits did on the environment.

> *Water was taken wherever and however it was found. The site for a new mission was determined, if possible, by the availability of at least some water which could be used to irrigate the land, either at the mission, or in a place several miles away. No effort was spared. In some places, water was brought half an hour's distance over irregular terrain through narrow channels or troughs carved out of the rock. At other locations, water was collected from six or twelve places—a handful from each source—and conducted into a single basin. Some swamps were filled with twenty thousand loads of stones and as many loads of earth. And sometimes just as many stones had to be cleared away to make this or that piece of land tillable. Nearly everywhere it was necessary to surround the water as well as the soil with retaining walls or bulwarks, and to erect dams, partly to keep the small amount of water from leaking out, and partly to keep the soil from being washed away by the torrents of rain. Even so, all the work was often useless. At best one had to patch and to repair every year, and sometimes it was necessary to start all over again* (Baegert 1979).

1.3. Elements of the construction: known plant and animal species

The main concerns of Jesuit fathers were the production of enough food for the maintenance of few soldiers and a small group of native people living there. Through the economical support of the *Fondo Piadoso* foundation and the always difficult work to have ships in good conditions to cross the Sea of Cortés (Crosby 1994), the missionaries brought to the oases in Baja California many new exotic plants that were adapted to growth under this environment. On relation with the introduction of new species on Baja California, father Baegert said.

> *Of European and German fruits, there were none in California except a few peach trees. From them, two rather small and stale peaches were once sent to me from a place thirty hours away* (Baegert 1979).

Corn and wheat were the most important crops in all the missions, nevertheless in some of them also olives, grapes, figs and dates were cultivated. There are also references about crops of beans, chick-pea, watermelon, melon, pumpkin, cotton, sugar cane, peach tree, banana, pomegranates, orange, lemon and other vegetables. The father Píccolo brought from Sinaloa roses and quinces, and sowed and harvested some rice (Del Barco 1973, Baegert 1979).

Cows, goats, horses, pigs, sheeps, and other domestic animals were introduced to supply food products that could not be obtained by the agriculture. The cattle were also used for the manufacture of candles and soap, ships and boats, shoes, saddles and bags. In the following sixty years, after the Loreto mission foundation, the *visitador* Ignacio Lizassoáin in 1761 reported 1500 to 4000 cows per mission and between 1000 to 4000 goats and sheeps (Del Río 2003). The harsh environment in the Peninsula made cattle growing difficult to practice into the missions; most of the livestock were left in freedom to find their own food in the desert. Baegert said about this, *The cattle had free passage and were permitted to wander fifteen and more hours in every direction to find their feed.* Even after the expulsion of the Jesuits, the amount of cattle that lived on wild was very high. The Franciscan Juan Ramos de Lora in 1768 said *if the cattle living in wild had been gathered, the problems of food, during the Jesuit period, had been resolved* (Del Río 1974).

Due to the absence of grass, the cattle introduced in Baja California fed itself mainly on the legumes and succulent plants of the desert. Baegert described the behavior of the cattle as follows, *They ate thorns, two inches long, together with stems, as though they were the tastiest of grasses.* The great amount of cattle introduced by the Jesuits and the lack of control on it brought a new ecological condition for the desert environment, the introduction of herbivore pressure exerted by large animals. Although there are no references about the impact of this condition, livestock could have significant effects on the ecosystem, changing the abundance and distribution of the species that they usually ate.

During the Jesuit period, the introduction of new plants, the water management, and the agricultural and cattle practices brought by the missionaries were the most important drivers for the colonization and the transformation of the Baja California Oases in the first forms of productive systems of the Peninsula. By the economical support of the southern missions in Baja California and the mission's ones in the continent, the Jesuits had time and some resources to explore new lands in the north. The information gathered along these explorations was very valuable for the knowledge of the natural resources of the Baja California Peninsula and for the colonization process to the north.

2. AFTER JESUITS PERIOD (1768–1900): DECLINE AND CHANGE

2.1. Property land changes after the missionary period

After the expulsion of the Jesuits from Baja California, the colonization and land management ran by civilian authorities and not by the religious order. In 1768, the Gálvez Instructions promoted the creation of new towns in the ancient missions (Piñera-Ramírez 1991). The Franciscan, who occupied the place of the Jesuits, continued having the control of the churches but the mission system disappeared and the cultivable lands around the churchs were slowly distributed among the civilian population, the Californios and the Franciscans. The land was divided in small yards and the people could take decisions on the land use, however, land property was uncertain delaying the colonization process and the development of the economical activities in the ancient missions.

It was until 1830 when the missionary organization finished and the land tenure of the oases passed to be property of the nation (Piñera-Ramírez 1991), that process permitted the authorities to give little more security on the land possession and the new settlers of the oases, mainly mestizos and descendants of Spaniards, began to raise cattle and to seed these lands of the oases in Baja California Sur.

Several missions were recognized like as towns in 1858 (San José del Cabo, Santiago, Miraflores, San Antonio, San Bartolo, El Rosario, Comondú, Loreto, San Javier, La Purísima, Mulegé, San Ignacio and Santo Tomás) and settlers began a new form of land tenure organization, in the *ejidos* (Piñera-Ramírez 1991). This communal form of land possession was used to take decisions on cattle management and some agricultural activities.

At the end of nineteenth century, 60% of the population lived in the south portion of the Peninsula (Deasy and Gerhard 1944) and the agriculture and cattle raising activity was more concentrated in this region. Besides the growing of vegetables, Mediterranean products like fig, grapevine, date and olive trees, as well as sugar cane were the most important crops in the villages of the southern region of Baja California Peninsula. Comondú and Mulegé were very important for its wine production whereas in San José del Cabo and La Paz it took place for the great amounts of sugar cane. In 1853, Rafael Espinosa and Francisco Xavier, published in the *Boletín de la Sociedad Mexicana de Geografía y Estadística* a description about the economy of the region. From southern Baja Californian, products like grapes, onions, potatos, sweet potatos and pitahayas were exported to Mazatlán and Guaymas, while, from the northern part, were obtained grapes, figs, dates, olives and wine, being the best, the wine that produced in San Ignacio. However, Baja California Peninsula followed continued not being non self-sufficient and products like flour, corn, beans, rice, chick-pea, lentil, sugar and others like clothes and materials for construction were brought by the ships coming from other parts of Mexico (Piñera-Ramírez 1991).

3. TWENTY CENTURY: OASES TRANSFORMATION CONTINUES

3.1. A comparative approach about land use changes

At the beginning of twentieth century, the Peninsula of Baja California was still, an inaccessible place that awakened curiosity on many explorers. Some of them left evidence by means of photographs that portray the landscape of the missions and the towns the Jesuits founded from the end of the 17th to the middle of the 18th century. In 2008, during my postdoctoral stay in the University of California in Riverside with Dr. Ezcurra, I saw the first time some of these photographs. We compared between the old and recently plates photographs taken in the same oasis, and were amazed about the land use changes that happened during the last century. It was for this reason that I devoted myself during that year to increase the photograph collection to be able to repeat it and to describe the land use changes that had happened on the last one hundred years.

Through the contributions of some collaborators—Exequiel Ezcurra, San Diego Natural History Museum (SDNHM) and University of California, Riverside; Stephen, Bullock, Centro de Investigación Científica y de Eduación Superior de Ensenada (CICESE); Juanita Ames and Jacobo Rousseau, settlers of San Ignacio, Baja California Sur; Javier Aguiar Zuñiga and Noe, settlers of Mulegé, Baja California Sur; and Nestor Agundez Martínez, Culture House Director in Todos Santos, Baja California Sur—and by means of the search in libraries, historical archives and Web pages—Fototeca de Monumentos Históricos, Mexico; Fototeca Nacional, Mexico; Library of SDNHM; San Diego Historical Society; San Diego Museum of Man; CalPhotos, Berkeley; Orpheus University of California San Diego; and US Geological Survey Photographic Library—I acquired a suite of 70 photographs of nine oases of Baja California Sur taken between *ca.* 1900 and 1970.

The repeated ground-based photographs technique was used for the first time in 1888 to describe landscape changes in glaciers (Turner *et al.* 2003). For the evaluation of vegetation changes, one of the most important research studies that used repeated photographs was published with the name of *The Changing Mile* in 1965, and then, with the name of *The Changing Mile revisited* between the late 1800s and the late

90s of the twenty century, were Raymond M. Turner and collaborators continued its long term commitment for the study of the landscape changes at the Desert Laboratory in Tucson, Arizona. The interpretation of matching pair photographs has been an excellent tool for the evaluation of vegetation changes (Bullock *et al.* 2005). Other recent tools like aerial photographs and satellite imagery have some advantages, such as, the large spatial coverage, however, the identification of the species composition is limited to only to the dominant ones. On the other hand, the first aerial photographs became available at the late 1920s and satellite imagery until at the early 1970s so, ground photographs are considered a better tool if long-term (longer than 100 years) studies are being planned.

On March 2008, I traveled with a group of collaborators to the oases of Santa Gertrudis, San Ignacio, Mulegé, Todos Santos, El Pescadero, La Purísima, San Isidro, Comondú, and San Javier; where we repeated the photographs that different photographers had obtained, sometimes, more than a hundred years ago. For a good match of the photographs, it was necessary to find exactly the place from which the photographers took them. Then, using the ArcGis 9.2 hardware, I have being compared the repeated ground photographs in order to define the land use categories in both of them, and estimated the changes in land cover.

3.2. Some tendencies on land use changes in the last century on Baja California Sur oases

In Baja California Sur, many people live in the oases where Jesuits founded the old missions. Like in the past, agriculture and cattle rising are still being important activities, but in some oases like San Ignacio, Mulegé and Todos Santos, the tourism become became and important industry at the end of the last century. This situation has incremented the pressure to obtain water and in some cases, the agricultural production has diminished due to the scarcity of this resource that is now used, preferably, for the touristic activities. Agricultural diversity that surprised travelers at the beginning of twenty century (Martínez 1947, Jordán 1951) has disappeared in the oases where tourist or other activities have developed, and instead of this agricultural landscape, *Washingtonia* palm, which surely grew in these oases before the arrival of the first settlers, is returning to occupy its place in the homegardens of the old missions. However, in some oases, the agricultural activity is still important. In the oases of Santa Gertrudis, Pescadero and San Javier, people are growing vegetables that sometimes, are selling in markets of organic products. The isolation of the oases of Comondú, La Purísima, and San Isidro, has promoted the abandonment of the towns. The production of grapevine, date and olive trees, that was very important in the past have disappeared. The sale of leaves and individual palm trees of *Washingtonia robusta* for touristic places is, nowadays, one of the most important activities in Comondú oases.

In general, the photographs of the oases in 2008 show more vegetation cover for two reasons; first, because agricultural lands diminished and water becomes a limited resource (based on the opinions of the settlements), people began to growth more plants in their home backyards. In the photographs of 2008 there are more trees and palms (*Phoenix dactylifera* and *Washingtonia robusta*) growing in the backyards areas of the houses than in the old photographs. Second, the old agricultural areas that were abandoned and were not occupied with houses nowadays are places where the native palm, *W. robusta* is growing. In particular from the comparative analysis of the photographs of Mulegé (see Figure 1), I found a positive growth rate of the urbanized area. Nowadays, the number of roads and houses has grown and occupy the area that was used for agriculture. From 1900 to 1959, the average area in the photographs of Mulegé that showed agricultural and agroforestry landscape was of 13.69%, but in 2008, the areas with polyculture agriculture have being reduced to only 1.88% of the photograph, whereas, monoculture agriculture have completely disappeared.

The harvest and sale of date fruits was a very important economical activity in the oases of San Ignacio, Mulegé and Comondú. However, the 2008 photographs of Mulegé, although do not show a reduction in the average cover area of date palms, the number of patches with *W. robusta* have been increased forming mixed palm trees. These are growing in those areas where only *P. dactylifera* grew in the past. The trade of dates has been reduced in the last years and replaced by other economical activities. In Mulegé it is probably that many people came to work for the tourist industry and thus, they abandoned their agricultural parcels.

Other vegetation areas that were modified in the second half of the twenty century in Mulegé were the desert areas that surrounded the towns, the river, and the mangroves. The 39.10% of the desert area in average estimated in the old photographs, in 2008 reduced to 25.45%. The towns in all the oases that I visited have grown in the last decades, and the areas of desert were occupied with houses and the home backyard vegetation. In 1913, 1931 and 1959, in the photographs of San Ignacio and Mulegé, big floods were registered. Probably, latter, these events were responsible of changes of the form of the rivers. At present the river of Mulegé has reduced their width and more sand banks are now exposed. The Mangroves have being reduced dramatically from 1.18% in the past to a cover area of 0.60% in 2008, and most of it have disappeared because of the construction of new roads.

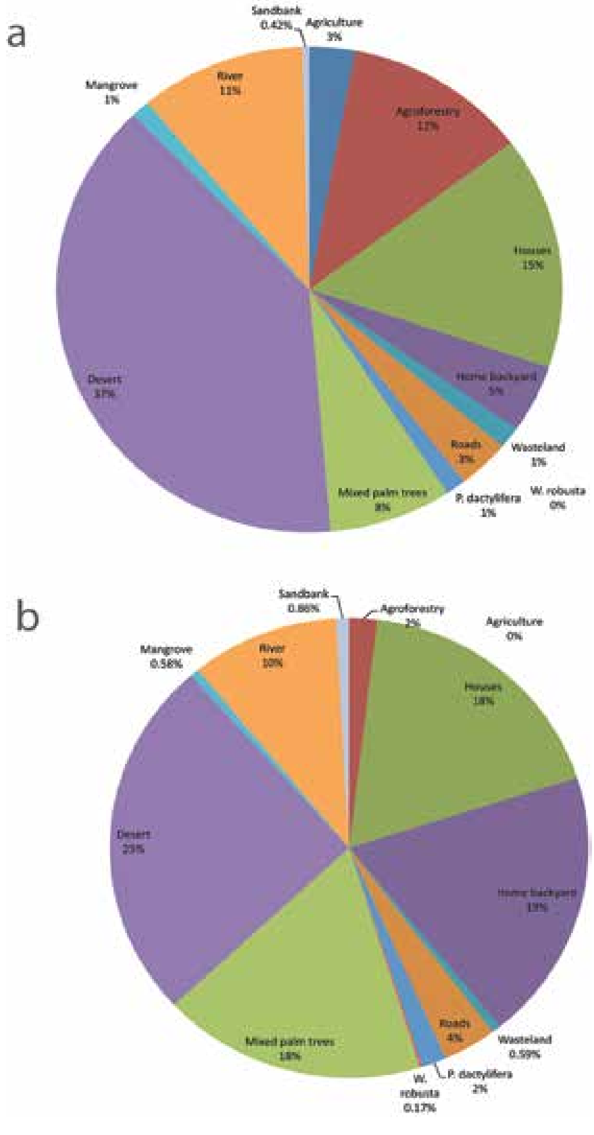
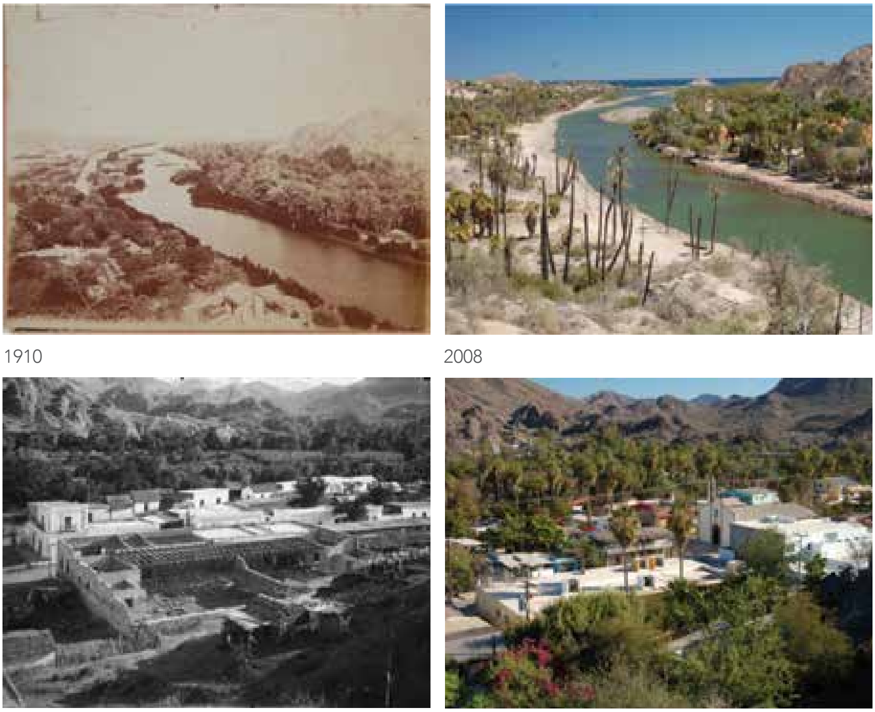


FIGURE 1. Historical land use changes in the oasis of Mulegé. (a) Past cover land use categories (%) from the area obtained in average from photographs taken in 1900, 1910, 1937, 1956, 1957 and 1959; (b) Present cover land use categories (%) from the repeated photographs taken in 2008. Land use categories were defined as; agriculture, agroforestry, houses, home backyard vegetation (trees, of *Washingtonia robusta* palms and *Phoenix dactylifera* palms), wasteland, roads, *P. dactylifera* palm trees, *W. robusta* palm trees, mixed palm trees (*W. robusta* and *P. dactylifera*), arid areas of desert, mangroves, river areas and sandbanks.



1910

2008

1900

2008

Pair photographs of Mulegé that show changes on the river and mangroves (above), and agricultural places replaced with mixed palm trees (bottom). The photograph of 1910 was taken by anonymous photographer and that of 1900, by Juan José Rousseau, a settler of San Ignacio, BCS. Carlos Martorell in collaboration with Pedro P. Garcillán and the author took the repeated photographs in 2008.

Although, before the conquest, these were important places for the survival of the ancient *Californios*, was until the Jesuits arrived when these oases becomes the first permanent inhabited places. The agricultural and cattle rising practices inherited from Jesuits defined the land use changes that nowadays we observed in the oases where they founded their missions. The biological diversity in the inhabited oases of Baja California is the result of several centuries of human activities in this region but one aspect of particular importance for the establishment in these places has been the presence of water and the management of this resource. The historical changes of the land use in the inhabited oases of Baja California can only be understood at the light of the human activities and also through the limitations that the environment has imposed to them in these places. We can say that these have been the drivers of the land use change in the oases of Baja California.

1957

2008

1959

2008

Pair photographs of Mulegé showing changes in agricultural land use, an increment in home backyard vegetation, and the size of the town (above). The impact of the 1959 flooding on the palm trees of Mulegé (bottom). The photograph of 1957 was taken by Dario Ruiz, a settler of Mulegé and that of 1959 by an anonymous photographer. Carlos Martorell in collaboration with Pedro P. Garcillán and the author took the repeated photographs in 2008.

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LIVING AT THE EDGE: THE BLUE FAN PALM DESERT OASES OF NORTHERN BAJA CALIFORNIA

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Plant species living at the limits of their distribution are likely to be particularly affected by climate change, and it is in these areas where significant plant variation, adaptation and migration usually occur. Information on the current processes that control the ecological dynamics of relict palm populations at the limit of their northwestern distribution in America is poorly known. We provide summarized information on what we know about the ecology of blue fan palm oases in the northern deserts of Baja California, and on the underlying mechanisms driving palm establishment and distribution in these highly fluctuating ecosystems. Since such riparian ecosystems provide vital ecological services for human and nonhuman life, the identification of these processes is critical to preserve biodiversity and water availability in the Central Desert in the face of ongoing environmental change.

1. INTRODUCTION

Plants living at the edge of any habitat are elements for the formulation of multiple questions for ecological investigations such as, why limits occur where they do? and how do marginal plant communities respond to them? Several disciplines such as, biogeography, demography, macroecology, reproductive biology, physiology and genetics should be integrated to provide adequate answers to these questions recognizing that ultimately, margins management depend on the manner of human perception on the nature of variation of plant populations. Marginal areas have experienced climatic changes in the past and, therefore, species living in these areas may be pre-adapted to such changes making them relevant in the study of species responses to fluctuating environments. In a scenario of a warmer world it is highly probable that changing climatic conditions will have a marked effect on plant geographical distributions, their responses to environmental alterations, particularly in marginal areas that withstand human exploitation. Thus, current interests in climate change have prompted different research projects into plants living at the margins (Crawford 2008).

Boundaries provide an interesting opportunity for observing limits to plant species survival, in the sense that these are not merely controlled by the impact of average probability of adverse climatic conditions, but also by the competition from other species and by the frequency of extreme events, such as drought, flooding, and freezing, which have been occurring for decades, centuries, or even millions of years ago, creating complicated patterns of distribution (Crawford 2008). At a more local scale, individuals at the margins of populations may be exposed to special spatial features influenced by their relationships with their neighbors which include a variety of factors such as pollen dispersal, seed production, gene flow and the availability of potential sites for establishment. Many of the adaptations that allow plants to live at the margins have evolved as means of overcoming limited access to resources; and one of the most common solutions is to reduce the energy demand or what is known as the *Montgomery effect* (Montgomery 1912), which states that in areas of low environmental potential, ecological advantage is conferred by low growth rates. Plant species in marginal habitats with fluctuating environments frequently show a high degree of polymorphism and provide a number of distinct ecotypes, described as a *balanced polymorphism,* that confer immediate fitness by increasing the ecological tolerance of the species as a whole (Crawford 1997). Examples of this phenomenon are visible in places where the constant risks of disturbance and environmental stress maintain a pronounced degree of polymorphism in plant populations (Crawford 2008).

Demographic limits to plant distribution include those factors that adversely affect recruitment or increase mortality. Demographic factors influencing plant distributions are not the property of species or populations, but are instead a function of habitat and location (Antonovics *et al.* 2001). The principles of *Island Biogeography* (MacArthur and Wilson 1967), that relate species numbers on islands to an equilibrium, clearly illustrate the necessity to consider the nature of the habitat and how it modifies recruitment and mortality rates, particularly at population margins where opportunities of recruitment and the hazards of extinction are different from core locations in demography studies. Between the factors that influence recruitment and mortality, the soil seed bank has its own demographic dimension, with embryos that lie dormant in the soil until there is an opportunity for them to germinate. Disturbance is included in demography since it affects both recruitment and mortality, and can have negative effects as it can destroy plant biomass and/or positive effects by providing new spaces for colonization or by aiding diversity through limiting the extent to which any species can permanently dominate a habitat. In this sense, plants that can withstand frequent and severe physical disturbances (*ruderals*) are expected to have been selected for an optimal set of characteristics including, size, growth pattern, resource storage, and reproductive strategies.

2. PALM SPECIES OF NORTHAMERICA'S NORTHWEST: THE DISTRIBUTION LIMIT OF A RELICTUAL VEGETATION

During the Cretaceous and Tertiary periods, and also during post-glacial times a particular flora was widely distributed in North America, approximately up to 65 degrees of latitude (Sankey *et al.* 2001). Woodrat (*Neotoma*) middens that contain remains of plants, invertebrates, and vertebrates have been used as a tool for tracking climate/vegetation changes and for the reconstruction of the past environments and climates (Wells 1976, Betancourt *et al.* 1990). A particular study in Baja California documented past relative plant abundances and distributions that were different from the modern ones (Sankey *et al.* 2001). Apparently, soil development on boulder surfaces and a relatively more mesic climate in this Peninsula, allowed plants to expand into marginal habitats. As the climate gradually turned out dry and hot at the end of the Miocene (12 million years ago), the vegetation restricted to the riparian habitats (Betancourt *et al.* 1990, Sankey *et al.* 2001, Wehncke *et al.* 2012b).

In the Central Desert region of Baja California vegetation patches from an ancient paratropical flora (Peñalba and Van Devender 1998), are found today as isolated climatic relicts on mountain tops and along canyons that still conserve wet conditions. Dominated by the blue fan palm, *Brahea armata*, these remote oases depend on intermittent water courses, and consequently on highly variable climatic conditions. In turn, they provide particular microclimatic conditions that support contrasting biotic communities and offer fundamental ecological services (Wehncke *et al.* 2009, 2010, 2012a, 2012b).

These palms correspond to the group of the Coryphoids, one of the five monophyletic groups (subfamilies) of the family Arecaceae (Bjorholm *et al.* 2005). While most palm lineages are currently widespread in the tropical and subtropical regions of the world, in congruence with the traditional association of the family with warm and moist climates, the geographical pattern of coryphoid species richness still seems to reflect its ancestral history, exhibiting a strong bias toward Central and North America (Corner 1966, Bjorholm *et al.* 2005, 2006). According to Bjorholm *et al.* (2006), coryphoid species richness seems to be least strongly controlled by the modern environment, but instead influenced by historical and regional factors. The endemic blue fan palm seems well adapted to this fluctuating environment, coping well with extreme aridity, summer heat, high direct solar radiation, and freezing temperatures (-12°C, www.floridata.com) with only minor foliage damage. Age estimates, using repeat photography methodology suggest a potential longevity that exceeds 500 years (Bullock and Heath 2006).

In the Central Desert, where many organisms live at or very near the threshold for surviving climatic extremes, the availability of oases with palm fruits arranged in patches and interspersed along canyons is critical for human and non-human subsistence (Wehncke *et al.* 2009, 2012b). Since palm oases are distributed as distinct patches in space and time, seed dispersal and post-dispersal seed predation processes both within and between oases are of great demographic importance (Wehncke *et al.* 2009). Likewise, because the seed dispersal syndrome of blue fan palms fruits seems to correspond to endo-zoochory probably performed by the now extinct Pleistocene mega-fauna (R. Felger, pers. comm.), their spatial distribution and ecological interactions with the present-day fauna are important elements in understanding the recruitment patterns of this species near the northern limit of the family's distribution in western North America (Wehncke *et al.* 2009, 2010). Commonly dominated by plants that live for decades and even centuries (Vasek 1980, Turner *et al.* 1995, 2003), the underlying mechanisms of desert vegetation dynamics are generally difficult to study (Whitford 2002).

3. ECOLOGICAL ASPECTS OF DESERT OASES ECOSYSTEMS

Spatial patterns in many desert plant populations and communities derive from the interplay of abiotic factors and of positive (facilitation) and negative (competition, predation, herbivory) biotic interactions (Callaway 1995, Miriti *et al.* 1998, 2001). Frugivory, seed dispersal, and seed predation processes may affect the resulting recruitment patterns and the ecological dynamics of plant populations (Jordano 1995, Herrera 1998, Thompson 2002). In addition to the biological processes, the physical structure of a system has its own spatial characteristics (Dungan *et al.* 2002), which influence palm population density and distribution (Wehncke *et al.* 2010). For example, flood regimes in rivers of arid regions determine groundwater conditions, therefore declines in flood intensity and frequency may change abiotic and biotic conditions within a floodplain, homogenize seed banks, and drive patch dynamics (Pickett and White 1985) producing well-defined vegetation patterns (Stromberg *et al.* 1996). The presence of surface attributes, rocks and soil properties are key elements in shaping water, nutrient, and seed fluxes that influence ecosystem structure

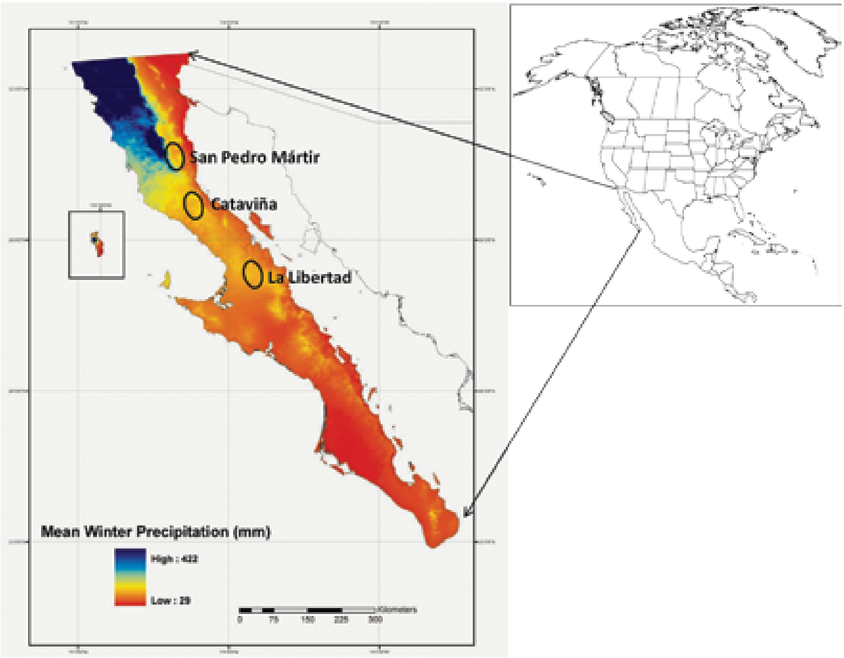

FIGURE 1. Location of study sites (San Pedro Mártir, Cataviña, and La Libertad) in northern Baja California, Mexico.

and dynamics (Poesen and Lavee 1994, Aguiar and Sala 1999, Maestre and Cortina 2002). Blue fan palm desert oases are probably one of such fluctuating environments in which seeds may be dispersed in two or more "phases", with different sets of dispersal agents involved on each one.

4. UNDERLYING ECOLOGICAL PROCESSESS AND PALM DISTRIBUTION PATTERNS

Here we summarized what is known about the ecological processes underlying the current distribution and structure of blue fan palm populations forming oases (Wehncke *et al.* 2009, 2010) in three mountain washes separated from each other approximately 200 km in a straight line (San Pedro Mártir [SPM]; Cataviña [CAT], and La Libertad [LL], see Figure 1). In each of these sites we established four plots of approximately 1ha in size (200 x 50 m) that constitute patches of vegetation along the canyons. We considered that each site represents a different population since the distances between plots were >30 m, but <3 km apart. Phytogeographically, the sites are found in two different subdivisions of the Sonoran Desert: the San Pedro Mártir site is located within Forrest Shreve's (1951) Lower Colorado Valley, while Cataviña and La Libertad are located within Shreve's Vizcaíno Region, also known as the Central Desert of Baja California. Sierra San Pedro Mártir is composed of large granite blocks that drop off sharply toward the eastern desert floor below. A number of east-flowing streams run along the escarpment fed by water collected as ice and rain in the higher elevations during the moist and cold winter months. Cataviña and La Libertad, are part of the Natural Protected Area Valle de los Cirios and are located on the Pacific slope of the Baja California ranges having a more tropical climate influence.

We used the actual spatial distribution of plants to explore the underlying processes that regulate plant populations and structure communities (*e.g.*, Greig-Smith and Chadwick 1965, Connell 1971, Janzen 1971, Wright and Howe 1987, Wehncke *et al.* 2010). We explored the importance of post-dispersal seed removal by vertebrates, recruitment, and distribution patterns of the blue fan palm in these canyons by evaluating (i) the levels of palm seed removal by vertebrates at two spatial scales and the initial fate of dispersed seeds, (ii) the spatial distribution and association of seedlings and adults at two spatial scales, (iii) seed removal levels and seedling densities based on density and distance to adult palm trees, and (iv) the age structure of the population (Wehncke *et al.* 2010). Although it is known that rodents and other seed-eating animals are abundant in deserts, we found that overall, levels of post-dispersal seed removal were low in all study sites (in 78% of cases, seeds were found intact, 7% corresponded to cases in which one half of the seeds was removed, and 15% to cases where both seeds were removed, N = 56). In general, postdispersal seed predation by vertebrates did not have a significant effect on blue fan palm establishment. However, small rodents and invertebrates were identified to be responsible for most of the blue fan palm seed removal/predation in this ecosystem (see Table 1). This is congruent with the absence of large vertebrates that could predate such hard seeds. Anachronistic traits still remain in blue fan palms, such as the spines along the petiole of the leaves representing defenses against non-existent browsers as well as, fruits and seeds that accumulate below trees that seem also unfit to the living fauna. Janzen (1986) suggested that after the megafauna extinction, plant species would contract to monospecific stands, each surviving only where habitat conditions are suitable and where it is not exposed to resource competition from others.

Spatial variation in seed removal levels by rodents was significant at regional but not at local scales, and this agreed with our expectations that seed predator communities may diverge in accordance with regional climate and biogeography (Lawlor 1983). However, since we registered similar species compositions of seed removers

TABLE 1. Vertebrate blue fan palm seed predator species registered during the studied period, in northern oases of Baja California, Mexico. Study areas: San Pedro Mártir (SPM), Cataviña (CAT), and La Libertad (LL). Sizes of seed predators (total length in millimeters): *Reithrodontomys*: (135–154; 64–85), *Peromyscus*: (220–285; 117–156), *Neotoma*: (225–383; 95–185), *Dipodomys*: (234–259; 135–161), *Perognathus*: (110–115; 53–83), *Chaetodipus*: (136–182; 70–103), *Tamias*: (208–240; 71–120), *Ammospermophilus*: (210–240; 71–83), *Spermophilus*: (357–500; 145–200).

Family	Species	SPM	CAT	LL
Muridae	*Reithrodontomys megalotis*	x	x	x
	Peromyscus californicus	x		
	Peromyscus eremicus	x	x	x
	Peromyscus eva			x
	Peromyscus fraterculus	x	x	x
	Peromyscus maniculatus	x	x	x
	Peromyscus truei	x		
	Neotoma lepida	x	x	x
Heteromyidae	*Dipodomys agilis*	x	x	x
	Dipodomys merriami	x	x	x
	Perognathus longimembris	x	x	
	Chaetodipus arenarius	x	x	x
	Chaetodipus formosus	x	x	x
	Chaetodipus penicillatus	x		
	Chaetodipus rudinoris	x	x	x
	Chaetodipus spinatus	x	x	x
Sciuridae	*Tamias obscurus*	x	x	
	Ammospermophilus leucurus	x	x	x
	Spermophilus beecheyi		x	
	Spermophilus cf. atricapillus		x	x
Total species		**17**	**16**	**14**

at the three sites (see Table 1), we suggest that regional differences in postdispersal seed removal and seed fate might rather result from distinct removal activity and behavior at each site as a result of differences in the physical characteristics of the three canyons. This also agreed with other studies that suggest that spatial variation in seed predation may arise because some habitats, irrespective of seed availability, are more suitable for certain granivores than others (Hulme and Benkman 2002). The distinct geomorphologic characteristics of each of the studied canyons, as well as the distribution of the vegetation cover, have the potential to affect post-dispersal seed removal activity by rodents and/or birds. One of our study sites, Cataviña, was characterized by wide canyons with less coverage of understory plants and/or rocks, providing rodents with limited hiding places, thus making them more visible and susceptible to predation. Such effect has the potential to restrict rodent movement patterns, and consequently their seed removal activities. Cataviña also showed the lowest seed removal values (see Figure 2a), though most of the seeds removed disappeared or were considered dead. The fate of removed seeds was significantly different among the three study sites (see Figure 2b). Frequently fewer seeds are removed from open microhabitats (Myster and Pickett 1993, Hulme 1997), and this appears to occur when rodents are the principal granivores, since their abundance is positively associated with vegetation cover (Hulme 1993). Seeds were removed from 0.5 up to 20m from the stations at La Libertad and from 0.5 up to 13m at Cataviña, 1m being the most frequent removal distance at both canyons (see Figure 2b).

Seedlings tend to establish near adults and their densities decline with distance from the adult palm (see Figure 3a, b) a tendency which was significant in all sites. In contrast, seed survival showed no significant association with adult densities or distance to the nearest neighbor adult plant, showing no variation in differential survival attributable to distances to adults (Wehncke *et al.* 2010). Based on this and the overall low levels of blue fan palm seed removal by vertebrates found in all sites, it seems that current post-dispersal seed removal by vertebrates does not have a significant effect on the establishment of the blue fan palm. A similar pattern emerged when using a Spatial Analysis by Distance Indices methodology (Wehncke *et al.* 2010). The weak positive association between seedlings and adults at the whole 'patch' level simply indicates that establishment tends to occur in or near those places where adults have already established successfully. More important, however, was that the analysis showed a negative association between seedlings and adults at the individual tree ('within the patch') level, indicating that within places where growth is most successful seedlings established preferentially in relatively open spaces. Their apparent affinity at the scale of the whole patch is probably caused by their co-occurrence in particular patches where local conditions are more suitable, possibly related to water availability.

The three blue fan palm populations studied showed marked regional differences in adult densities and distributions (adult densities: AD, and nearest-neighbor distance: NND, were used as measures of adult distributions and were found to be significantly different among sites, but not significant among plots nested within

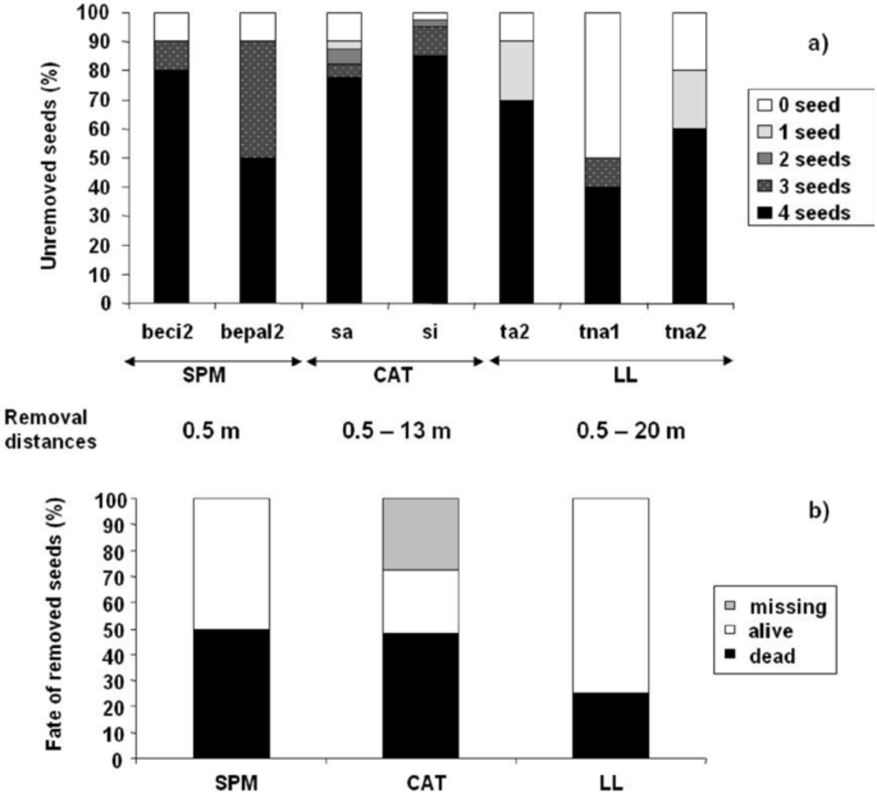

FIGURE 2. Patterns of seed removal: (a) percentages of cases with zero, one, two, three, and four seeds left at each site and plots within sites. San Pedro Mártir (SPM) included beci2 and bepal2 plots, Cataviña (CAT) included San Antonio (sa) and Santa Inez (si) plots, and La Libertad (LL) included ta2, tna1, and tna2 plots; (b) range of distances (meters) of blue fan palm seed removal by vertebrates (using the method of colored threads) and percentage of cases in which removed seeds were missing, dead or alive in each site.

sites (see Wehncke *et al.* 2010). Cataviña had the lowest AD and the highest NNDs measured from randomly placed points; La Libertad represented the intermediate case; and San Pedro Mártir showed the highest ADs and the most aggregated adult palm distribution (see Figure 3a, b). In contrast with adult distributions, seedling densities were only marginally different among populations or sites, but markedly different among plots within sites (Wehncke *et al.* 2010). This may reflect a more local dependence of seedling establishment on the different canyon physiography at each site. In arid and semiarid climates, and particularly in desert blue fan palm oases, where precipitation can be flashy (sudden, erratic, intense, and of short duration),

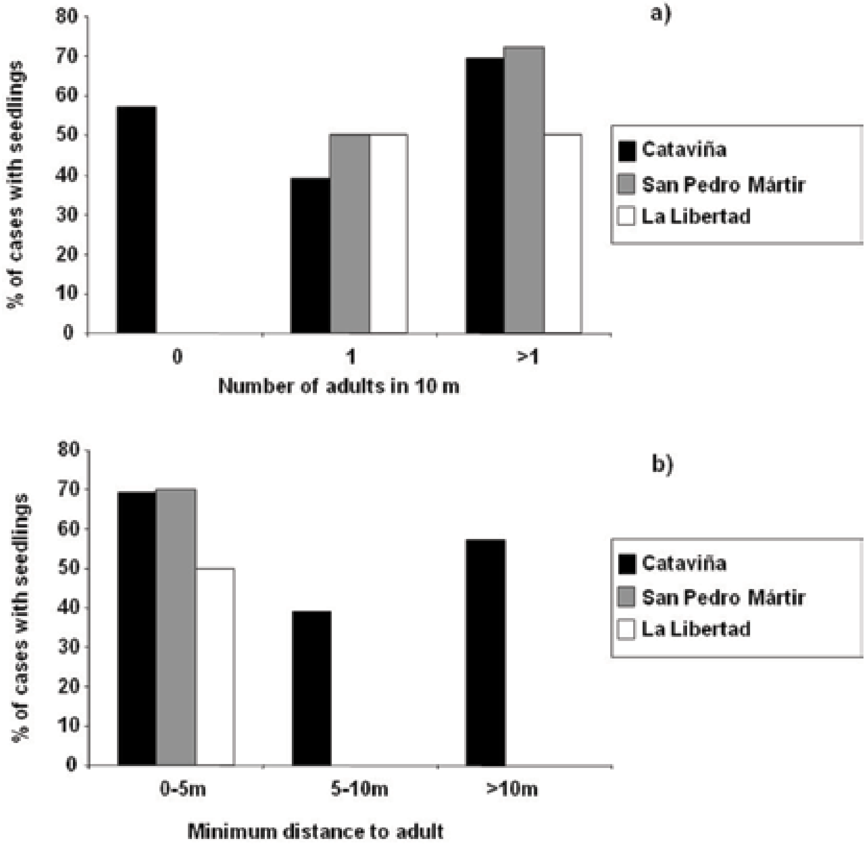

FIGURE 3. (a) Percentages of random points with seedlings (area: 0.0007ha), for each adult density category (AD: 0, 1, and >1 adults), and (b) at each nearest-neighbour distance category (NND: 0-5 m, 5-10 m, >10 m), in the sites of San Pedro Mártir, Cataviña, and La Libertad.

channels are susceptible to extensive erosion. Such disturbances often remove large amounts of streamside vegetation and sometimes entire adult palms, produce abrupt depositional changes, and disrupt community propagule banks (Wehncke unpubl. data, Briggs 1996).

The presence of nurse plants and/or nurse objects, as well as the canyon physiography at each site may have the potential to affect post-dispersal seed removal activity patterns by rodents, as well as to provide vital protection for palm seedling establishment from the extreme flood pulsing. Although the micro-environmental conditions prevailing in shaded microhabitats may be an important factor that enhances seed germination, nurse objects such as rocks and channel sand bars exert a

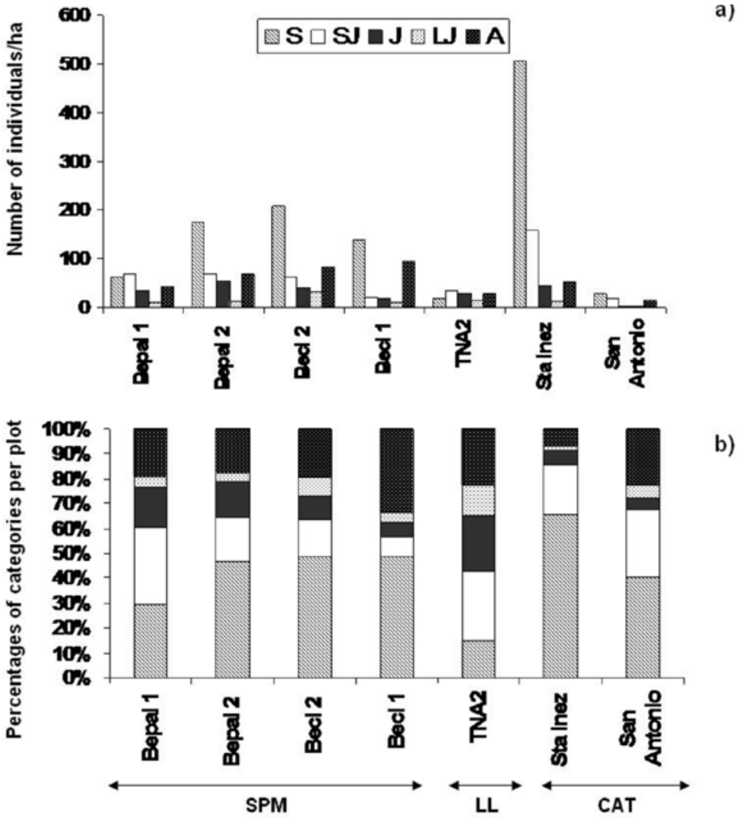

FIGURE 4. (a) Number of blue fan palm individuals per hectare at each age category, and (b) distribution of age categories (percentages of each category per plot) in study plots and sites. San Pedro Mártir (SPM): Bepal1, Bepal2, Beci2, Beci1 plots; La Libertad (LL): TNA2 plot; and Cataviña (CAT): Santa Inez and San Antonio plots.

significant protecting effect to palm seedlings from the extreme pulsing stream flow in these canyons. Preliminary demographic results showed that the highest number of seedlings occurred in a channel sand bar in Cataviña canyon (density individuals/ha = 508, see Figure 4). Annual leaf production in individuals of up to 0.5 m tall also showed the highest values at this sand bar (mean = 6 ± 4.3 new leaves, N = 39, Wehncke unpubl. data). Additionally, in April 2007 we counted the total number of seedlings below a particular focal adult palm individual located at the limit of the sand bar. In the absence of water a seedling shadow of 370 seedlings extended up to 13 meters of distance from the adult tree, with a southwestern orientation following the direction of the stream. We observed that most of the seedling shadows below

FIGURE 5 (CLOCKWISE). (a) Seedling shadow on Cataviña sand bar, (b) Ongoing seed germination experiment in Cataviña sand bar, (c) Seed germination experiment in the laboratory.

trees (n = 20) had the same orientation in this plot. We visited the site again after eight months and found that all these seedlings disappeared or dried out. The next time we saw any seedling below the same focal tree again was in February 2009 (see Figure 5a).

In this desert ecosystem seeds can form part of the soil seed bank and apparently wait until adequate conditions allow them to germinate. In an ongoing germination experiment in October of 2008, 300 blue fan palm seeds distributed in three treatments were planted directly in the field on the sand bar of Cataviña (see Figure 5b). One hundred palm seeds were taken from diverse animal feces, 100 were planted with the whole fruits, and 100 without the fruit pulp corresponded to control seeds. After approximately four years of setting the experiment no germination has been registered. Likewise, germination experiments of blue fan palm seeds performed in the laboratory showed that from 120 seeds that were collected in September of 2006 and planted during the following days of collection only 4 (3.3%) germinated between July and August of 2008 (see Figure 5c).

Based on the previous observations on seedling emergence and the seed germination experiments performed in the laboratory, we could suggest that blue fan palm seeds tend to germinate after a two year period. However, based on the field germination experiments we could expect that this long-lived palm species may probably require a long time in the seed bank. Finally, we suggest that any protection against extreme solar radiation, mechanical damage, and flooding, and/or sand accumulation in such changing ecosystems might enhance palm seedling survival and determine seedling distribution patterns.

5. CANYON PHYSIOGRAPHY: A SIGNIFICANT PHYSICAL ASPECT IN CURRENT BLUE FAN PALM POPULATION STRUCTURE AND INTERACTIONS

It seems that the geomorphology of granite canyons and the associated water regime might be a significant factor on the palm population structure of these oases. In the San Pedro Mártir site—a deep narrow canyon with steep walls—adult palm density was the highest, while in the flat arroyo wash of Cataviña—an open sandy area with lots of available space and the formation of mid-channel bars that provide safe sites for seedling establishment—total palm seedling densities were the highest of the three sites (see Figure 4). Bar formations have important influences in the life cycle of many riparian plant species (Briggs 1996). Bars, generally composed of sand and/or gravel, are largely determined by the stream flow and influence the geometry strength of flow (Heede 1980). Overall, and judging by their population structure where all life-history categories were adequately represented within each site, the blue fan palm populations in the three oases seemed to be in a fairly good conservation state.

Seeds may escape from predation near seed sources due to the considerable homogenizing effect of the stream flow, but also due to significant levels of seed dispersal by vertebrates. Results from a study on the spatial association patterns between frugivorous birds and blue fan palms in two natural palm patches of Baja California and at different spatial scales showed that blue fan palms function as important sources of fruits, seeds and shelter for a great number of animals at the individual tree level and at the patch scale (Wehncke *et al.* 2009). Blue fan palms are important focus of resources for a great number of animals that use these oases as corridors, bringing seeds as they move and connecting isolated populations of palms. The vector which was probably responsible for relocating most viable seeds was the pulses of overland water flows which transported seeds downhill and eventually determined the pattern of adult distributions we currently see along drainage lines. Nevertheless, not all blue fan palms were distributed in this way; endozoochorous seed dispersal was evident in these canyons, especially at the peak of fruiting seasons. Since seed dispersal in desert canyons may be mainly governed by episodic events of winds and water flows through landforms and topography, the estimation of the qualitative and quantitative importance of palm seed dispersal by animals is relevant to start understanding 'multidirectional' (as opposed to 'unidirectional') forces of dispersal that may influence the occurrence and maintenance of this desert riparian ecosystem. Palms commonly seen growing from crevices on cliffs indicate that dispersal must also take place uphill. There is a diverse array of present-day blue fan palm seed dispersers that consume the thin and sweet mesocarp (Wehncke *et al.* 2009). Among them, ravens, jays, woodpeckers, pumas, lynxes, coyotes, foxes, skunks, bighorn sheep and mule deer have been observed to use canyons as sources of water and food, taking seeds in their movements from lowlands to uplands therefore connecting isolated palm populations. The importance of processes acting at small scales cannot be excluded, since significant beetle predation on seeds was detected below the palms (Wehncke *et al.* 2009).

Also during the flowering period, myriad of insect species visit palm flowers constituting what can be defined as several oases within oases, but also insect predators can be detrimental for palm populations. The interaction between the larva of an endemic moth, *Litoprosopus bajaensis*, and this endemic blue fan palm was documented in these oases, registering that palm populations were severely impacted by this larva, causing high damage to the inflorescences (Wehncke *et al.* 2012b). Again, Cataviña showed the highest reproductive success of palms and consequently, an important proportion of stems escaped from the herbivore predation. This study highlights the role of desert oases as resource patches and connectivity pathways for mobile insects, but also the effects of different water flow dynamics and water pulses in providing an opportunity window of escape from predation for host plant species living in desert environments.

6. FINAL REMARKS

In such fluctuating ecosystems there may be more than one kind of limitation to plant survival, *e.g.*, physiological, demographic, and/or reproductive, and therefore long-term records of demographic data are necessary to discern the causes of failure of populations to maintain their numbers. Marginal areas present a challenge to successful reproduction and thus, a wide range of different strategies have evolved to overcome disturbance through natural causes such as flooding and erosion, and many other aspects of environmental uncertainty. For example, in desert plants the maintenance of variation appears to be a common strategy for long-term survival. In many vegetation communities, anachronistic plants seem to be heading toward a long-term decline (Johnson 2009). Although several examples of plants with megafauna fruit syndromes in Central and North America show distributions restricted to lowlands and flood plains, reflecting their current reliance on gravity and water to move abrade large seeds (Janzen and Martin 1982, Barlow 2000), dominant blue fan palms seem to be very well adapted to this fluctuating ecosystem. These populations provide ecosystem structure, and act as the source of multiple interactions with the present-day fauna; therefore, changes in their distributions can be expected to have cascading effects on the entire ecosystem.

Such riparian ecosystems embedded in arid environments influence human and nonhuman life, providing fundamental ecosystem services, regulating water regimes, and acting as sources of biodiversity. The values of these functions to human society depend on a complex set of relationships between oases and the surrounding environment. The increase in population and the importance of water for human development will work against effective conservation of wetlands in deserts. Since measurements of the frequency or magnitude of such degradation have not been attempted to any significant degree, an important challenge for conservation in deserts is the understanding of their oases ecosystems dynamics. We expect that this baseline information will help in further investigations and encourage management actions to preserve these wonderful last water reservoirs.

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FLORISTIC ANALYSIS IN OASES AT CENTRAL BAJA CALIFORNIA SUR

José Luis León de la Luz*

One of the features of the Sierra de la Giganta Mountains is the existence of many small riparian wetlands (oases) along pluvial drainage channels. There are no geohydrological studies from which to determine their dynamics in their arid environment, but these areas confront increasing water extraction to satisfy demands of small local settlements. This study compiled a checklist of the hydrophytes from 12 representative oases, and discusses their current status on the basis of composition, richness, and plant species characteristics. We performed a classification of locations based in absence-presence of 57 species using UPGMA to represent a dendrogram of sites group cohesivity. Two major kinds of locations were revealed. By analyzing individual site characteristics, we found that one group fits to places under "low impact conditions" and the other composed of locations that are "impacted" in several ways. The former group contains oases that are relatively rich in species, including aquatic forms which seem to be the most sensitive to disturbance. Geographical affinity of the whole floristic list reveals that most species have a broad distribution, mostly in tropical America.

Keywords: Baja California, Sierra La Giganta, desert wetlands, hydrophytes.

1. INTRODUCTION

The southern half of the Baja California Peninsula is part of the southern Sonoran Desert Biotic Province (Shreve and Wiggins 1964). The Cape Region, at the southern tip of the Peninsula, has been floristically documented and is considered a separate region from the desert communities (Wiggins 1980, León de la Luz *et al.*

1999). The Sierra de La Giganta, northern neighboring region of the Cape Region, has been recently described by León de la Luz *et al.* (2008), concluding that it has sufficient characteristics to be considered a distinct eco-region of the desert (Shreve and Wiggins 1964, Wiggins 1980, Brown 1994).

The relative low altitude of the mountains and the narrow width of the southern Baja California Peninsula provide little surface area for hydrologic depressions. Annual rainfall ranges from 100 to 300 mm. A number of oasis, wetlands, or permanent waterways (springs, seeps) and seasonal reservoirs, locally called 'pozas' or 'tinajas,' occupy this land. No perennial river or lake is currently present (Grismer and McGuire 1993), although in the early 20th century, streams near San José del Cabo and Mulegé were considered "small rivers" (León de la Luz *et al.* 1997).

Currently, numerous small water bodies have been identified, some of them isolated and others occurring in close groups (Maya *et al.* 1997). The largest and best known oases are San Ignacio, Comondú, La Purísima, Mulegé, and San José del Cabo. Some of these are close to the sea; others are spring-fed from the mountains. There are no geo-hydrological studies from which to determine their dynamics. Several are vanishing in the last few decades because water is being extracted to satisfy demands of local settlements. It is likely that the demise of these wetlands results from the combination of primary extraction and increased aridity in the region during the very recent Holocene (Spaulding and Graumlich 1986, Díaz *et al.* 2001).

Most of the riparian habitats are located in an area of the Sierra de La Giganta (Maya *et al.* 1997) where only a few thousand people live and whose livelihood depends on this water supply. Primary activities of the population are extensive livestock ranching of cattle and goats, subsistence agriculture, and gathering mesquite logs (*Prosopis palmeri* S. Wats. and *P. articulata* S. Wats.) for making charcoal (León de la Luz and Domínguez 2005). In a hypothetical model, rainfall collected in upland basins enters aquifers that supply water to the lowlands for supporting scattered farms, rural settlements, and small agricultural areas. Increasing demands for water to satisfy local needs is usually pumped from these aquifers. The importance of these areas for local settlements is obvious.

These oases are attractive areas for vertebrate fauna. Álvarez *et al.* (1996a) found that nearly 65% of the mammalian species in the south-central part of the Peninsula visit the Sierra de La Giganta oases. At ten oases, Rodríguez-Estrella *et al.* (1997) found an edge effect, with resident and over-wintering migratory birds. Álvarez *et al.* (1996b) recorded 32 species of reptiles and amphibians, of which nine are endemic to the Peninsula and ten are adapted to mesic environments or live in association with water sources. Plants of the scrubland community are usually found along the stream banks and weed-like plants arrive from nearby agricultural areas. Cultivated species, such as the date palm (*Phoenix dactylifera* L.) are also found at the wetland margins.

Since many aspects of oases vegetation are unknown, the main objectives of this study were to: 1. Compile a checklist of hydrophytes in a representative group of wetland locations in the Sierra de La Giganta; 2. Describe the current status of these wetlands, using composition, richness, and species characteristics; 3. Describe geographic relationships of the hydrophytes; and 4. Describe the threats to preserving native plant life, in contrast to the exotic plants species that are also present at the oases.

2. MATERIAL AND METHODS

2.1. Study site

The Sierra de La Giganta is part of the geological backbone of the northern part of the Mexican state of Baja California Sur. It is an elongated and asymmetrically-shaped over its 150-km length and trends SE-NW. The crest or spine lies relatively close to the Gulf of California, with some peaks reaching more than 1,000 m (1,600 m Cerro Giganta, 1,200 m Cerro Mechudo) and many others reaching elevations over 800 m. The drainage divide averages less than 8 km from the eastern shoreline of the Peninsula, leading to precipitous escarpments and steep slopes along the Gulf of California. The western flank slopes more gradually, finally draining gently onto the Pacific coastal plain. Riparian wetlands appear sporadically along the western drainage channels. Some arroyos are about 100 km long (see Figure 1). Most of the Sierra de La Giganta structure is composed of repeating layers of volcano-clastic sandstones of Miocene age (Comondú Formation) and conglomerates of more recent epochs. Extensive alluvial slopes and plains occupy the western flanks.

The climate ranges from BWh to BSh (K√ppen classification). On the western side of the divide, Mission San Xavier (25°51'N, 111°32'W, 420 m), which is the highest weather station in the range, receives 300 mm rainfall (García 1973), while the next closest weather station at El Pilar (24°28'N, 111°00'W, 90 m) receives only 125 mm. Hastings and Turner (1965) consider this sector as transitional between the summer monsoonal-type rainfall regime, typical at the southern third of the Peninsula, and the winter cyclonic regime that prevails in the northern half of the Peninsula. This does not mean that the Sierra receives rainfall in the extreme seasons; on the contrary, this is a transitional region that usually receives little rainfall in summer or winter. Mean annual temperature ranges from 19 to 22°C; winter temperatures are relatively mild, with a few days of frost (García 1973).

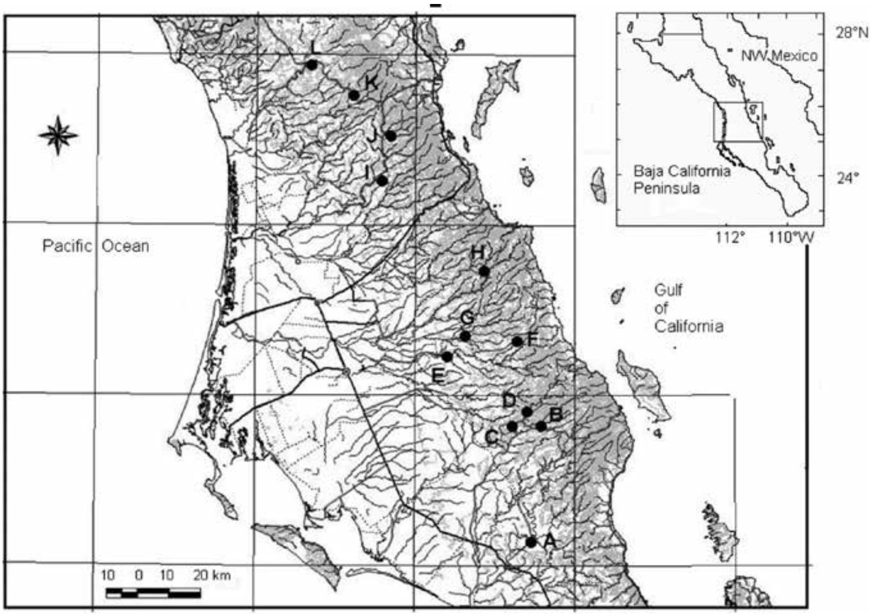

FIGURE 1. Location of 12 oases in the Sierra de la Giganta in the central Baja California Peninsula of Mexico. Names of oases are listed in Table 1. Note drainage systems.

In the entire Baja California Peninsula, 184 oases have been identified, 171 located in the southern half (Maya *et al.*1997). Each was assigned to one of seven groups. Group III (54), mostly in the Sierra de La Giganta, are intermittent, small water bodies within arroyos, ranging from 0.05 to 0.59 km^2 in area, and most of them contain fan palms *Washingtonia robusta Wendl*, and date palms *Phoenix dactylifera*.

2.2. Field inventory

We studied 12 of the larger riparian wetlands in the Sierra de la Giganta, all having a permanent water supply (see Figure 1). From March 2001 through July 2002, physical and biological characteristics of each wetland were inventoried. Several geographical factors (distance to the nearest human settlement, number of inhabitants, and size of water body) were also recorded in several ways (see Table 1). Some indicators of human impact were also recorded (see Table 2).

Riparian zone boundaries were defined according to Thompson *et al.* (2002) as the ecotone where facultative and obligate aquatic plants (the hydrophytes) comprised >50% of species present. This zone coincides with soil that remains moist during the driest season (March through July). Having delimited our sampling area, we

TABLE 1. Characteristics of 12 oases located in the Sierra de la Giganta in the central Baja California Peninsula of Mexico

*Based on nearest weather station.

**Distance from the nearest human settlement (rancho, village, or town).

@According to local informants.

‡Based on local distribution of hydrophytes.

	Oases	Location NW	Arroyo	Elevation (m)	Rainfall* (mm)	Distance ** (m)	Inhabitants @	Surface‡ (km^2)	No. of species
A	El Pilar	24°28' 111°01'	El Pilar	140	125	20	16	0.25	20
B	San Pedro de la Presa	24°51' 110°59'	San Pedro	270	180	30	68	0.10	21
C	Cantarranas	24°51' 111°05'	San Pedro	250	180	500	12	0.17	33
D	Santa Ma. Toris	24°54' 111°02'	La Presa	250	170	400	26	0.16	25
E	Tepentú	25°05' 111°19'	La Picota	130	150	300	18	0.47	16
F	La Ensenada	25°08' 111°04'	La Ensenada	425	220	200	8	0.09	14
G	El Rosario	25°09' 111°15'	Batequitos	240	185	300	14	0.17	19
H	Poza del León	25°22' 111°11'	San Juan	410	220	100	6	0.19	34
I	El Edén	25°40' 111°33'	San Xavier	110	170	1000	8	0.28	34
J	La Fortuna	25°49' 111°31'	San Xavier	480	300	300	12	0.57	29
K	Palmar Las Bebelamas	25°57' 111°39'	San Venancio	400	285	300	8	0.68	28
L	San Miguel Comondú	26°03' 111°48'	Comondú	450	300	10	330	0.88	26

identified and recorded each plant species as obligate hydrophyte (aquatic plant) or facultative (plants from the adjacent scrubland).

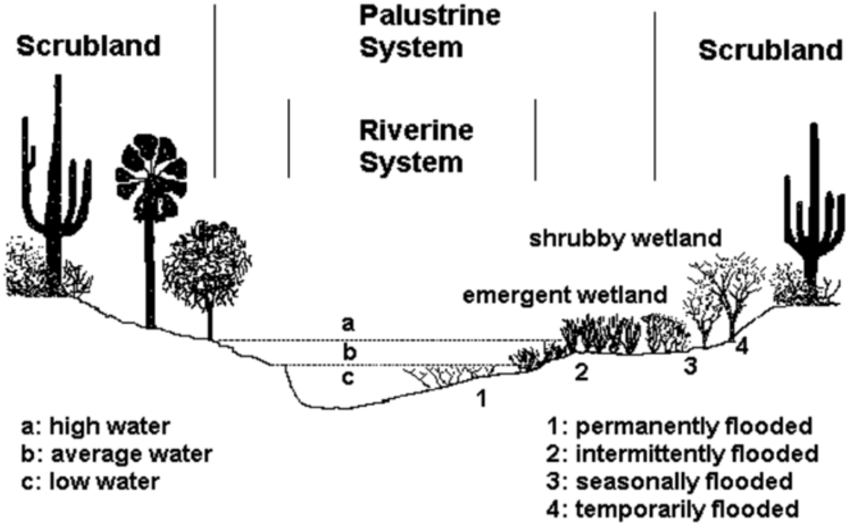

FIGURE 2. Distinguishing features, habitats, and vegetation in an idealized cross-section of an oasis in the Sierra de La Giganta (modified from the wetland classification of Cowardin *et al.* 1992).

Stem growth was used to classify hydrophytes species in eight classes (arborescent, simple, stoloniferous, rhizomatous, floating, rooted/submerged, rooted/emerged, or prostrate); stem form includes three classes (herbaceous, woody, or semi-woody); and growth phase includes two classes (perennial or seasonal). Most of the species were identified on site; but some plants were not readily identified in the field since they did not show flowers and/or fruit. These were preserved and later identified using published regional floras (Shreve and Wiggins 1964, Wiggins 1980, Gould and Moran 1981, Turner *et al.* 1995, Felger 1999, 2000).

2.3. Numerical analysis

We used a multi-variate analysis for a presence-absence or incidence matrix (57 species × 12 sites), each element containing a designation 1 (present) or 0 (absent). A classification based on floristic attributes at the sites was based on a hierarchical cluster analysis generated with MVSP v3.1 software (Kovach 2007); the clustering method was the UPGMA (unweighted pair-group using arithmetic averages). The Euclidean distance was used as the measure of similarity between sites.

2.4. Biogeographical analysis

Geographic affinity of 57 obligated hydrophytes, at the species level, was obtained from the natural distribution of the taxa cited in several floristic studies (Shreve and

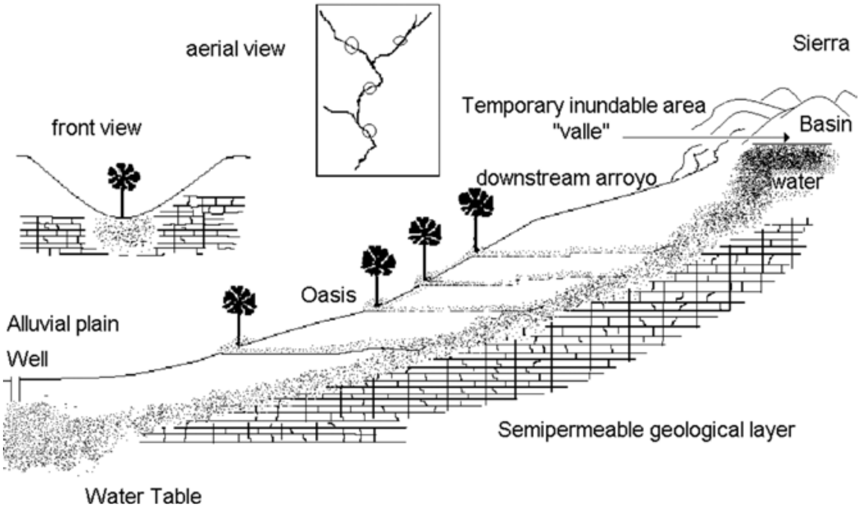

FIGURE 3. Idealized geohydrological scheme of the Sierra de la Giganta oases in the central Baja California Peninsula in Mexico. Rainfall is captured in elevated closed basins, where it percolates to the subsoil. By artesian pressure or cracks, water emerges in the oases intermittently until reaching phreatic surface in the alluvial plains.

Wiggins 1964, Wiggins 1980, Gould and Moran 1981, Felger 2000). The geographical range of each species was classified as either: regional endemism, peninsular, northwestern Mexico, Mexico, North America, continental America, tropical America, pantropical, or cosmopolitan.

3. RESULTS

3.1. General assessments

Figure 2 is an idealized profile diagram of a Sierra de La Giganta oasis, which is based on a wetlands nomenclature found in Cowardin *et al.* (1992). Figure 3 is a schematic representation of the geo-hydrological model of oases. Thus, each oasis is part of a discontinuous series of slightly depressed relief along a rocky arroyo bed having a 3–5° slope and the oases appear near the outlet of an artesian spring. Water level in oases vary throughout the year, depending on current rainfall and occurrence of rainfall in previous years, evaporation rates, runoff from the upslope drainage basin, and extraction for farming and other human activities. Characteristics of the oases are shown in Table 1. The size of the oases was obtained from Maya *et al.* (1997) or by our field surveys. Extent of the oasis site depends on the distribution of hydrophytes, particularly palm groves. Disturbance in an oasis is assessed by using

TABLE 2. Indicators of human disturbance in 12 oases in the Sierra de La Giganta in the Baja California Peninsula of Mexico. (Location codes are identified in Table 1).

Oases												
Type of human disturbance	A	B	C	D	E	F	G	H	I	J	K	L
1. Associated agricultural practices	x	x			x	x	x					x
2. Evidence of cattle ranching	x	x	x	x	x	x	x	x	x	x	x	x
3. Water extracted by pumping		x			x							x
4. Aggressive exotic plants present	x	x					x					x

TABLE 3. Stem growth forms of hydrophytes at 12 oases in the Sierra de la Giganta of the central Baja California Peninsula of Mexico.

*All seasonal or annual /biennial.

**Four perennials, one annual.

Environment	Growth form	Number of species	%
Terrestrial	Underground stolon	8	14.1
	Rhizomatous	11	19.3
	Herbaceous simple*	15	26.3
	Ligneous (Tree/ shrubby)	2	3.5
	Prostrate/ decumbent**	6	10.6
Aquatic	Floating	3	5.2
	Stem emergent	3	5.2
	Stem submerged	9	15.8
Total		57	100.00

four management conditions, of which some were observed during the fieldwork. Table 2 summarizes the evaluation of each oasis.

3.2. Vegetation

Species that are widely occurring in scrublands areas grow opportunistically on moist soil near the oases; these facultative hydrophytes include: cardon *Pachycereus pringlei* (S. Wats.) Britt. & Rose, choya *Cilyndropuntia cholla* Weber, and otatave *Vallesia glabra* (Cav.) Link, lomboy *Jatropha cinerea* (Ortega) Muell.-Arg., mezquite

Prosopis articulata S. Wats., vinorama *Acacia farnesiana* (L.) Willd., bledo *Celosia floribunda A. Gray*, apan *Bebbia juncea* (Benth.) Greene, and several other species. The obligate hydrophytes and the oases where they occur are listed in Table 4. The list includes 57 vascular plants (30 dicotyledons, 26 monocotyledons, and one fern). The survey of Arriaga *et al.* (1997) contains a list of 184 species in eight oases, but only 24 are obligate hydrophytes (according to our classification); all of them were found in this survey.

Of the 57 vascular species, 35 are perennial and 22 are seasonal (annual). Table 3 organizes the flora by life form. Most of the annuals are weeds, probably some of them came from nearby agricultural fields (Santo Domingo Valley). Based on consistence of the stem, 47 species are herbaceous, 7 are partly woody, and 3 are woody. The best represented families, in terms of species, are: Cyperaceae (12), Compositae (7), Scrophulariaceae (4), Onagraceae (4), and Potamogetonaceae (3). Of the Cyperaceae, seven species occur in the genus Cyperus. Table 3 displays this flora according to a classification of the form of stem growth, with 28% living in standing water and 72% in moist and wet soil.

3.3. Statistical analysis

The phenogram of these sites is derived from the UPGMA analysis (see Figure 4). Because the paired and grouped clusters in the phenogram result in linkages at different levels of similarity, an ecologically meaningful classification is not automatically indicated. UPGMA analysis indicates that distances between locations are strongly related to the heterogeneity of the matrix of distance, with the threshold of 5.1 linkage distance defines two large clusters. Cluster I contains oases C, I, H, J, and K, and Cluster II contains oases A, B, D, E, G, F, and L.

Cluster I contains 28 to 34 species at each oases; Cluster II contains 14 to 26 species at each oases. Also, analysis of the list reveals that a group of 33 species appear between one to five times in the records and another group of 24 species appear between six to eleven times in the records.

Some sites in each cluster constitute tight pairs. Locations C and I have almost the same number (33 and 34) and types of species. Locations E and L have different numbers of species (16 and 26), but all records from location E are practically included in location L (see Table 4).

Clusters I and II have another pair of sites that form well-differentiated subgroups, each pair with almost the same number of species, but only ~50% are the same species. These are locations J (29 species) and H (28 species) in Cluster I. Locations A (20 species) and B (21 species) occur in Cluster II. Site D in Cluster II is an

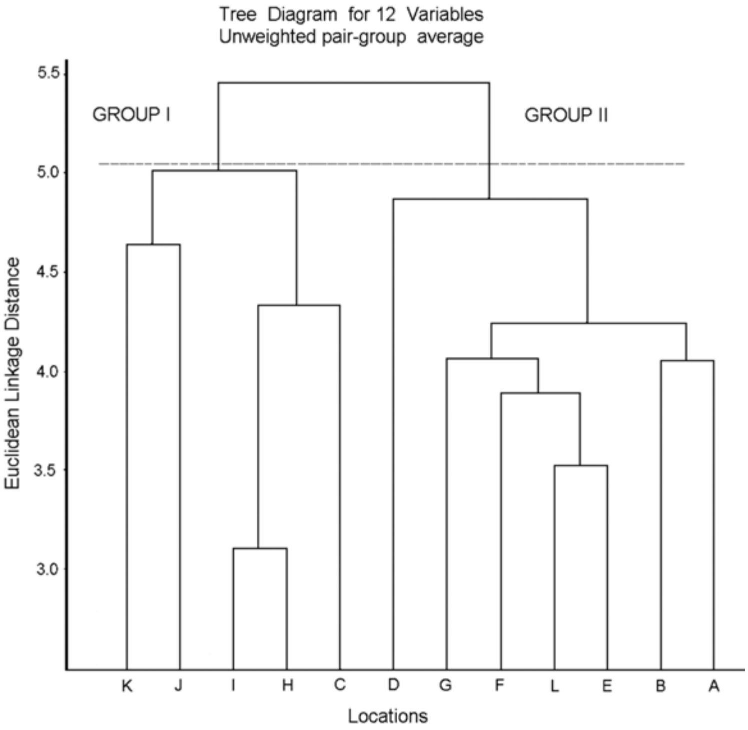

FIGURE 4. UPGMA phenogram based on a distance matrix comparison among several oases (A to L). Names of oases (locations) are listed in Table 1. See text for explanation.

interesting location, distantly linked to other sites in the cluster (high dissimilarity), yet suggesting an intermediate position between the two clusters.

3.4. Floristic interpretation

From the total number of species (57), Cluster I contains 49 and Cluster II contains 50 species. Species that consistently appear in the five locations of Cluster I are yerba-santa *Anemopsis californica* (Nutt.) Hook. & Arn., *Bacopa monieri* (L.) Wettst., *Mimulus dentilobus* Rob. & Fern., *Stemodia pussilla* Benth., *Echinodorus berteroi* (Spreng) Fasset, and *Polygonum hydropiperoides* Michx. Also, six combinations of four species appear jointly among the five locations and five possible combinations of three species appear together. At the seven locations in Cluster II, there are only two common species: buena mujer *Chloracantha spinosa* Benth. and the fan palm (palma real) *Washingtonia robusta*. In this cluster, a couple of species appear jointly in six locations and another two in two locations.

TABLE 4. Floristic list of obligated hydrophytes in 12 oases in the Sierra de La Giganta in the central Baja California Peninsula, Mexico. Names of the oases (A to L) are listed in Table 1.

Oasis	I	C	H	J	K	L	D	P	A	G	E	F
Ferns												
Marsilea vestita Hooker & Grev. (Marsiliaceae)	0	1	1	0	0	0	0	1	1	0	0	1
Dicotyledons												
Ambrosia ambrosioides (Cav.) Payne (Compositae)	1	1	1	0	0	1	1	0	1	0	1	0
Ammania coccinea Rottb. (Onagraceae)	1	1	0	0	1	0	0	0	0	1	0	0
Anagallis arvensis L. (Primulaceae)	1	0	1	0	0	0	0	0	0	0	0	0
Anemopsis californica (Nutt.) Hook. et Arn. (Saururaceae)	1	1	1	1	1	1	0	0	0	0		0
Baccharis glutinosa Pers. (Compositae)	1	0	1	1	1	1	0	1	1	1	0	1
Bacopa monieri (L.) Wettst. (Scrophulariaceae)	1	1	1	1	1	1	1	1	1	1	1	0
Centaurium capense Broome (Gentinaceae)	1	1	1	1	0	0	0	1	0	0	0	0
Centunculus minimus L. (Primulaceae)	0	0	0	0	1	0	0	0	0	0	0	0
Chloracantha spinosa (Benth.) Nesom var. *spinosa* (Compositae)	1	1	0	0	0	1	1	1	1	1	1	1
Eclipta alba (L.) Hassk. (Compositae)	0	0	0	0	0	1	0	1	0	1	1	1
Epilobium adenocaulon Haussk (Onagraceae)	0	0	0	0	0	0	0	0	0	1	0	0
Eustoma exaltatum (L.) Griseb (Gentianaceae)	1	0	1	1	1	0	1	1	1	1	0	0
Heimia salicifolia H.B.K. (Lythraceae)	0	1	0	1	0	1	0	0	1	1	0	1
Heliotropim procumbens Mill. (Boraginaceae)	1	1	1	0	1	1	0	1	0	1	1	0
Hydrocotyle umbellata L. (Apiaceae)	1	1	1	0	0	0	0	0	0	0	0	0
Hymenoclea monogyra Torr. et A. Gray (Compositae)	0	0	0	0	0	1	1	0	1	1	1	1
Kosteletzkya digitata A. Gray (Malvaceae)	0	0	0	0	0	1	0	0	0	1	1	1

Oasis	I	C	H	J	K	L	D	P	A	G	E	F
Ludwigia octovalvis (Jacq.) Raven (Onagraceae)	0	0	0	1	1	0	1	0	1	1	0	0
Ludwigia peploides (H.B.K.) Raven (Onagraceae)	1	1	1	0	0	0	0	0	0	0	0	1
Mecardonia vandellioides (H.B.K.) Pennell (Scrophulariaceae)	0	1	0	1	1	0	0	1	0	0	0	0
Mimulus dentilobus Rob. et Fernald (Scrophulariaceae)	1	1	1	1	1	1	1	1	1	0	1	0
Petunia parviflora Juss. (Scrophulariaceae)	0	0	1	0	0	1	0	1	1	0	0	0
Pluchea odorata (L.) Cass. (Compositae)	1	1	0	0	1	1	0	0	0	1	0	1
Polygonum hydropiperoides Michx. (Polygonaceae)	1	1	1	1	1	0	0	0	0	0	0	0
Roripa palustris (L.) Bess. (Cruciferae)	0	1	1	0	0	0	1	0	0	0	0	0
Salix bonplandiana H.B.K. (Salicaceae)	0	0	0	0	0	0	0	1	1	0	1	0
Samolus ebracteatus H.B.K. (Primulaceae)	0	0	0	0	0	1	0	0	0	0	0	0
Stemodia pusilla Benth. (Scrophulariaceae)	1	1	1	1	1	0	1	0	0	0	0	0
Tillaea erecta Hook subsp. *erecta*	0	0	0	0	0	0	0	0	0	0	1	0
Xanthium strumarium L.	0	0	0	1	0	0	1	0	0	0	0	0
Monocotyledons												
Cyperus cuspidatus H.B.K. (Cyperaceae)	1	0	1	0	0	1	1	0	0	0	0	0
Cyperus dioicus I.M. Jhtn. (Cyperaceae)	0	1	1	1	0	0	0	1	0	1	0	0
Cyperus esculentus L. (Cyperaceae)	0	1	0	1	1	0	1	1	1	0	0	1
Cyperus laevigatus L. (Cyperaceae)	1	0	1	1	1	1	0	0	0	1	0	0
Cyperus perennis (M.E. Jones) O'Neill (Cyperaceae)	1	1	0	1	0	0	1	0	1	0	0	0
Cyperus surinamensis Rottb. (Cyperaceae)	0	0	1	0	1	1	1	0	0	0	1	0

Oasis	I	C	H	J	K	L	D	P	A	G	E	F
Cyperus tenuis Swartz (Cyperaceae)	1	1	0	1	1	1	0	1	0	0	0	0
Echinodorus berteroi (Spreng.) Fasset (Alismataceae)	1	1	1	1	1	0	1	0	0	0	0	0
Eleocharis geniculata (L.) R. et S. (Cyperaceae)	1	1	1	0	0	1	1	1	1	0	1	1
Eleocharis montevidensis Kunth (Cyperaceae)	0	1	0	1	0	1	1	0	0	0	1	1
Fuirena simplex Vahl (Cyperaceae)	1	0	1	0	1	0	0	0	0	0	0	0
Hemicarpha micrantha (Vahl) Pax (Cyperaceae)	0	1	1	1	1	0	0	0	0	0	0	0
Juncus acutus L. (Juncaceae)	0	0	0	1	1	0	0	1	0	0	0	0
Juncus mexicanus Willd. (Juncaceae)	1	0	1	0	1	1	0	1	1	1	1	0
Lemna minor L. (Lemnaceae)	1	1	1	1	0	0	1	0	0	1	0	0
Naias guadalupensis (Spreng.) Morong (Najadaceae)	1	1	0	1	1	0	0	0	1	0	0	0
Naias marina L. (Najadaceae)	1	1	1	1	0	1	1	0	0	0	0	0
Phragmites australis (Cav.) Steud. (Gramineae)	0	0	0	1	1	1	1	1	1	0	1	1
Potamogeton illinoensis Morong (Potamogetonaceae)	1	1	1	1	0	0	0	0	1	0	0	0
Potamogeton pectinatus Raf. (Potamogetonaceae)	1	1	1	0	1	0	1	0	0	0	0	0
Ruppia maritima L. (Ruppiaceae)	1	1	0	1	0	0	1	0	0	0	0	0
Scirpus americanus Pers. (Cyperaceae)	1	0	1	0	1	0	1	0	0	0	0	0
Typha domingensis Pers. (Typhaceae)	0	1	1	1	1	0	0	1	0	0	0	1
Typha latifolia L. (Typhaceae)	0	0	0	0	0	1	1	0	1	1	0	0
Washingtonia robusta Wendl. (Arecaceae)	1	1	1	0	1	1	1	1	1	1	1	1
Zannichellia palustris L. (Potamogetonaceae)	1	1	1	1	0	0	0	0	0	0	0	0

TABLE 5. Geographical affinity of hydrophytes from 12 oases in the Sierra de La Giganta of the central Baja California Peninsula of Mexico, based on data from relevant floras (Shreve & Wiggins 1964, Wiggins 1980, Gould & Moran 1981, Turner *et al.* 1995)

Geographical region of affinity	Number of species	%
Baja California Sur	1	1.7
Baja California Peninsula	2	3.5
Northern Mexico	7	12.2
Mexico	4	7.1
North America	10	17.5
Tropical America	17	29.9
Pantropical	2	3.5
Cosmopolitan	14	24.6
Total	57	100.0

A subset of seven species appears only at oases in Cluster I and do not occur in Cluster II: *Anagallis arvensis* L., *Fuirena simplex* Vahl, *Hydrocotyle umbellata* L., *Centunculus minimus* L., *Polygonum hydropiperoides* Michx., *Hemicarpha micrantha* (Vahl) Pax, and *Zannichelia palustris* L. Another subset of eight species appears only at oases in Cluster II and do not occur in Cluster I: *Eclipta alba* (L.) Hassk., *Epilobium adenocaulon* Hausk, *Samolus ebracteatus* H.B.K., *Hymenoclea monogyra*, *Kosteletzkya digitata* A. Gray, *Salix bonplandiana* H.B.K., *Typha latifolia* L., and *Tillea erecta* Hook subsp. *erecta*. The most common species in these oases are *Mimulus dentilobus* Rob. & Fern., which grows at all five Cluster I oases and six of seven Cluster II oases, and *Washingtonia robusta*, growing at the seven Cluster II oases and four of the five Cluster I oases.

Table 5 shows the geographical affinities of the 57 species, according to comments in the regional floras. The degree of geographical affinity demonstrates the expected results: that the broader the geographic area, the greater the number of species it contains. Tropical regions of the Americas and the cosmopolitan element contribute the largest number of hydrophytes. The most restricted plant, *Centaurium capense* Broome, is an herbaceous annual that occurs statewide.

4. DISCUSSION

A revision of the of Sierra de La Giganta oases is required within the ample concept of wetlands. These central Baja California Sur oases are found in intermittent stream channels that are subject to periodic flooding, as well as receiving year-round spring or seep water (see Figures 2 and 3). Small wooded areas with emergent marsh-like vegetation arise under those conditions. In a general classification, these areas are called wetlands (humedales by many Mexican conservationists working on the Baja California Peninsula). In central Baja California Sur, arroyo wetlands are characterized by the regional endemic fan palm *Washingtonia robusta* and the non-native date palm *Phoenix dactylifera*, considered by conservationists as invasive in riparian habitats of the Sonoran Desert.

These oases are environmentally different from those described by Ezcurra *et al.* (1988) for coastal sand dune oases in the central Sonoran Desert, but seem to be similar in some grade to the wetlands in canyons described by Wehncke *et al.* (2009) in the northern Baja California Peninsula, as well with those cited by Felger (1999) in locations in the Sonoran Desert of mainland Mexico where they are called xero-riparian habitats. While they are in the same biotic province, these four situations are separated by hundreds of kilometers and are decidedly different from each other in floristics, micro-climatic and geo-hydrological conditions. In this sense, the wetlands of the Sierra de La Giganta seem to be unique in the Sonoran Desert Biogeographical Region.

In a general classification of wetlands, Lugo *et al.* (1988) and Cowardin *et al.* (1992) mention that regular catastrophic floods and ecological limitations are common in these riparian wetlands, leading to low species diversity and a relatively simple structure, compared to adjacent plant communities. Moreover, establishment and growth of plants are limited by environmental factors that seem to control composition and other processes in the vegetation. Among these factors are: periodicity of floods and droughts, occasional high kinetic energy of flood water, and low concentrations of nutrients in the soil. Hence, the fundamental niche for each species is largely affected by water dynamics and nutrients. Flooding from heavy rains, particularly from hurricanes and tropical storms that encounter the mountain range are the most drastic events affecting the oases. Human disturbances over the last three centuries should be included in the study of these habitats, especially in the last few decades when fuel-powered water pumps made water uptake easier, including developing small-scale agricultural activities (see Table 2).

Cluster analysis suggests a relative cohesivity among several hydrophytes. There are prevalent species associated with each cluster, each with a core of associated species. Sites that are part of Cluster I seem to be better conserved than those in Cluster II because they have larger surface areas, support fewer inhabitants, and are located farther from larger settlements (see Table 1). Also, analyses of data in Table 2 show fewer impacts to sites in Cluster I.

The 16 aquatic plants suggest less impacted conditions. An oasis with aquatic forms, such as the strictly hydrophytes, indicates some or all of the following conditions: sporadic cattle grazing, limited agricultural activity, no pumping of water, and a sufficient distance from settlements to make exploitation unattractive. Cluster I sites have hydrophytes, such as: *Echinodorus berteroi* (Spreng) Fasset, *Hydrocotyle umbellata* L., *Zannichellia palustris* L., *Typha latifolia* L., *Naias guadalupensis* (Spreng.) Morong, *N. marina* L., *Potamogeton illinoensis* Morong, *P. pectinatus* Raf., and *Ruppia maritima* L. Cluster II have hydrophytes such as *Chloracantha spinosa* (Benth.) Nesom var. *spinosa*, *Washingtonia robusta* Wendl., and *Typha dominguensis* Pers. Three aquatics are shared: *Marsilea vestita* Hooker & Grev., *Roripa palustris* (L.) Bess., and *Baccharis glutinosa* Pers.

Biogeographically, these oases contain hydrophytes with broad geographic distributions, having geographical affinity with the American tropics and worldwide; hence, these hydrophytes possess a relative broad environmental tolerance, but they need fresh water as a primary condition of survival.

Interestingly, the fan palm *Washingtonia robusta*, a native of this habitat, is now cultivated in subtropical and Mediterranean climates worldwide. This palm has great importance as the primary source of fronds for rustic roofing (palapas) in much of the Baja California Peninsula because the leaves are waterproof and sun resistant. Exotic plants growing at the oases that deserve mention are "carrizillo" *Phragmites australis*, used as a rustic building material, and date palm *Phoenix dactylifera*, introduced by Jesuit missionaries in the 17th century. Currently, almost all oases have some date palm groves, and scattered palms are seen along many watercourses. So far, no management plan exists for enhancing quality and quantity of date palms to diversify the economic base of the local inhabitants.

Some of the annual species are considered native weeds in this region, such as the huizapol grass *Cenchrus palmeri* Vasey that occur as scattered bunches within the oases, as well as dangerous exotics of recent arrival, such as the invasive buffel grass *Pennisetum ciliare* (L.) Link. Although these plants displace native species, they provide significant forage for livestock. The most aggressive exotic plant is the rubber vine *Cryptostegia grandiflora* (Roxb.) R. Br. (Asclepiadaceae), a serious threat to all Sierra de La Giganta oases. It is a fast-growing, climbing perennial that propagates by comose seeds and rhizomes. Although a native of Madagascar, in Australia it is considered one of the most dangerous exotics because it displaces native plants along waterways. It is currently being controlled by an expensive eradication program (ADA 2001).

5. CONCLUSIONS

Cluster analysis reveals that the hydrophytes are usually found in two distinct groups. Species within Cluster I occupy relatively better preserved habitats. Floating and stem-emergent aquatic life forms are included in this group. Species within Cluster II occupy impacted sites of several types and aquatic life forms are almost absent.

The high threshold of dissimilarity used to define the two clusters indicates floristic heterogeneity among the oases, although there are a small set of species typical to each group. Floristically, the wetlands suggest enduring dynamically-changing composition and structure, a condition that is being strongly modified by contemporary environmental impacts.

The oases of the Sierra de La Giganta are regularly affected by disturbances of different magnitudes, some of them catastrophic, particularly extraordinary floods from major storms and hurricanes that strike the mountains, but also extreme droughts, livestock trampling, and overgrazing. Water extraction, fire, and other human disturbances are associated with small-scale agriculture and extensive ranching. In this survey, there was no opportunity to find two oases that were similar in physiognomy. The pattern we found suggests that the floristic composition is a result of their particular history of disturbance.

A large proportion of these hydrophytes have broad geographical distribution, mainly in the American tropics. Mexican civil authorities should develop management plans to preserve and regulate water use in these areas. Particularly important for conserving species diversity is exclusion of cattle from these wetlands and encouraging primary activities that are sustainable. Date palm cultivation could be one of the most compatible activities. Also, there is an urgent need to develop a control and eradication plan for the invasive rubber vine *Cryptostegia grandiflora*, which is displacing all types of native plants.

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CURRENT DISTRIBUTIONAL STATUS OF SEVEN INVASIVE EXOTIC FISHES IN THE PENINSULA OF BAJA CALIFORNIA

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The current distributional status of seven invasive exotic fish species (*Gambusia affinis*, *Poecilia latipinna*, *Poecilia reticulata*, *Xiphophorus hellerii*, *Cyprinus carpio*, *Lepomis cyanellus* and *Tilapia* sp. cf. *zillii*) for the continental waters of the Baja California Peninsula was documented. This study was based on specimens collected between 1977 and 2011 for 109 sites, as well as records of species reported in the literature. In the oasis ecosystems of Baja California Sur is notable the impacts of the redbelly tilapia (*T.* sp. cf. *zillii*) and guppy (*P. reticulata*) on the endemic populations of the Baja killifish (*Fundulus lima*), while in the Lower Río Colorado basin of Baja California both redbelly tilapia and sailfin molly (*P. latipinna*) have decimated the remnant populations of the desert pupfish (*Cyprinodon macularius*).

Keywords: exotic fish, invasive fish, impacts, Baja California Peninsula.

1. INTRODUCTION

One of the main threats affecting the stability and integrity of the fish communities in the arid and semiarid regions of northern Mexico is the introduction of exotic or nonnative fishes (Contreras-Balderas *et al.* 2008). In Mexico at least 113 exotic fish species have been reported (Contreras-Balderas *et al.* 2008), number that will be increasing if programs of control and eradication of exotics are not timely implemented. The stability of the freshwater ecosystems with low species richness become chaotic when invasive exotic species (high competitive and ecological plasticity) are stocked, particularly in small wetland habitats as springs and oases, where its native biota that has evolved in isolation for thousandths of years and lacking competitive strategies and no predation are displaced or eliminated by this advantage interaction (Douglas *et al.* 1994).

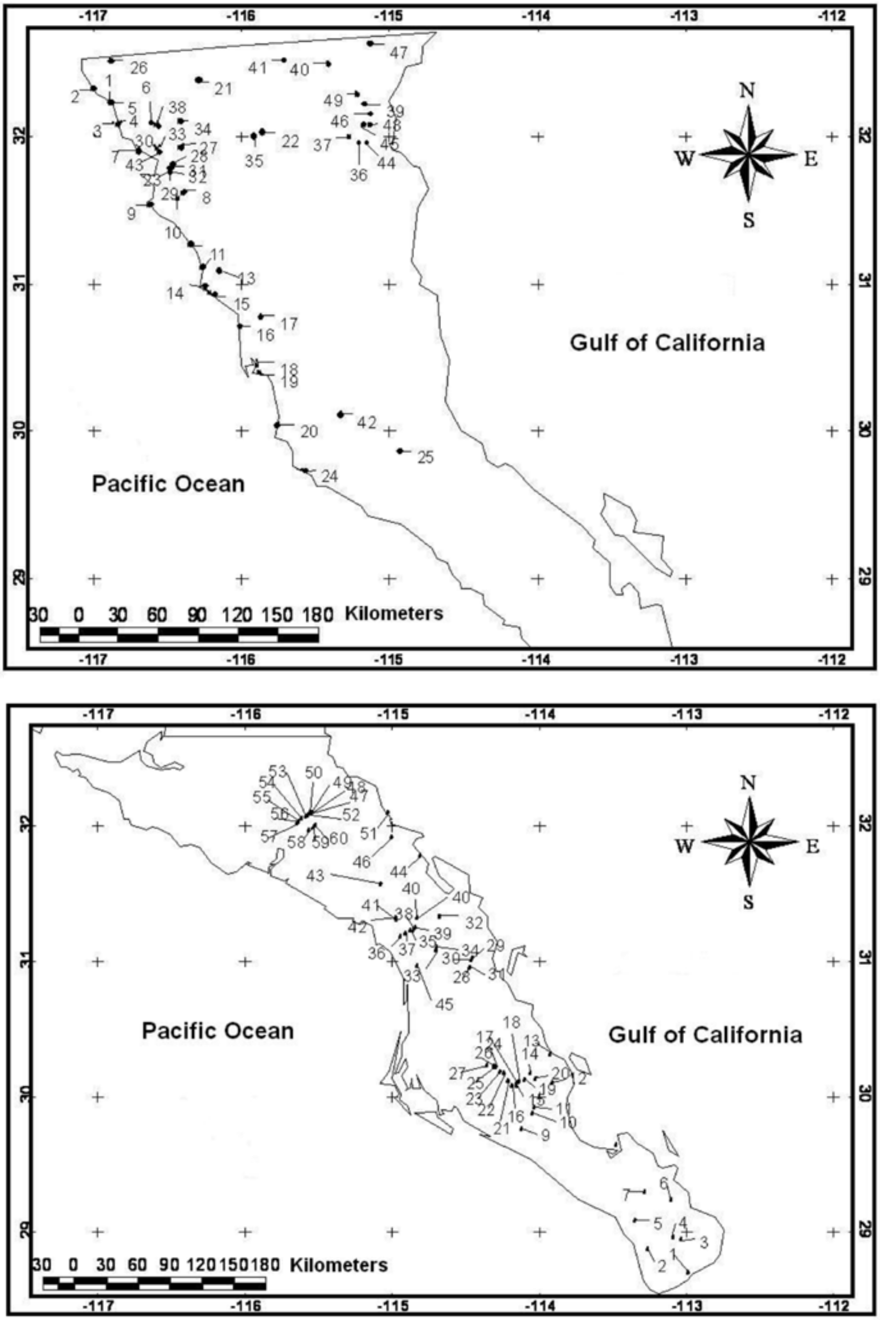
The homogenization of the biota in a geographic region is the result of the gradual elimination of the native species and its replacement by those exotics, which originates a loss of the biodiversity and changes in the function of the ecosystem (Mack *et al.* 2000, McKinney and Lockwood 1999, Marchetti *et al.* 2001, Rahel 2002). From a regional point of view, 17 exotic fish species has been reported for Baja California (Ruiz-Campos and Contreras-Balderas 1987, Ruiz-Campos *et al.* 2000) and six species for Baja California Sur (Ruiz-Campos *et al.* 2002, Ruiz-Campos 2012). Varela-Romero *et al.* (2002) evaluated the impact of exotic redbelly tilapia (*Tilapia* sp. cf. *zillii)* on the native populations of the desert pupfish *Cyprinodon macularius* in different sites of the lower Colorado River basin of Sonora and Baja California. These authors consigned the extirpation of the native pupfish for several historic sites of its distribution in Baja California (cf. Follett 1960, Hendrickson and Varela 1989). Likewise, Ruiz-Campos *et al.* (2006, 2008) evaluated the impact of redbelly tilapia on the distribution and abundance of the endemic Baja California killifish *Fundulus lima* in the oases of the San Ignacio and La Purísima of Baja California Sur, determining the virtual elimination of the endemic fish in the type locality of oasis San Ignacio.

The aim of this work is to document the distribution of seven exotic fish species and their impacts on the native fish fauna in the Baja California Peninsula, based on records with voucher specimens from scientific collections or records that been referred to in the literature during a period of 34 years.

2. MATERIAL AND METHODS

The records of distribution for the seven exotic species documented in this study were based on voucher specimens (cf. Appendix 1) that have been collected by the authors during a period of 34 years (1977 to 2011) in 109 sites through the Peninsula of Baja California, Mexico (see Figures 1 and 2, Appendix 2). The fish were captured using different types of fishing gears according to the habitat of each species. In shallow habitats (< 1.5 m deep) active (seine of 6 m long x 1.5 m height x 1/8 and 1/16 inches mesh size) and passive (minnow-traps) capture methods were used; while in those sites deeper than 1.5 m experimental gillnets (with 6 m-panels with mesh sizes of 0.5, 1.5, 3 and 4 inches) and cast nets were used. Electrofishing equipment (Smith-Root 15-C P.O.W.) was used for shallow habitat with low salinity (< 0.5 ppt), such as in the headwaters of streams (Sierra San Pedro Mártir).

Samples for each collected fish were fixed in field with a 10% formalin solution and transported to laboratory for analysis and identification. After seven days, the fish samples were washed with water during 1 day, and finally preserved with 50%



FIGURES 1 & 2. Collecting sites in the State of Baja California, Mexico (see details on toponomy in Appendix 2) / Collecting sites in the State of Baja California Sur, Mexico (see details on toponomy in Appendix 2).

ethanol. Voucher specimens were deposited in the following Fish Collections: Facultad de Ciencias, Universidad Autónoma de Baja California (UABC); Departamento de Investigación Científica, Universidad de Sonora (DICTUS); and Facultad de Ciencias Biológicas, Universidad Autónoma de Nuevo León (UANL).

The voucher specimens of fish species collected in the study area previous to 1991 were examined in the following museums: Facultad de Ciencias Biológicas, Universidad Autónoma de Nuevo León (UANL) at Monterrey, NL (Mexico); Centro Interdisciplinario de Ciencias Marinas (CICIMAR) at La Paz, BCS (Mexico); and Museo Regional de Historia Natural-Universidad Autónoma de Baja California Sur (UABCS) at La Paz, BCS.

Scientific and common names and taxonomical arrangement of the species follows to Eschmeyer (1998). For each species a synopsis is provided that includes the following information: *Common name:* common names of the species both in English and Spanish based on Nelson *et al.* (2004). *Native range:* native distribution range of the species based on published records. *Previous records:* those records referred to in publications or in museum records prior to 1991. *Recent records:* those collection records supported with voucher specimens deposited in the UABC Fish Collection or with visual reports, all of them carried out during samplings after 1991. Other information appears in parenthesis. *Comments:* information regarding to the non-native distribution of the taxon, as well as documentation of the impact of this exotic species on the distribution and abundance of the native fish fauna.

3. RESULTS AND DISCUSSION

The following seven invasive exotic species documented here, represent those species with higher distributional representation in the Baja California Peninsula.

Family Poeciliidae

Gambusia affinis (Baird & Girard, 1853)

COMMON NAME: Mosquito Fish / pez mosquito.

NATIVE RANGE: Atlantic and Gulf of Mexico drainages from south New Jersey to Mexico; Mississippi river basin from central Indiana and Illinois, USA south through the Gulf of Mexico drainages and northern Veracruz (Álvarez del Villar 1970: 111; Page and Burr 1991: 235).

PREVIOUS RECORDS. Baja California: Río Hardy at Meganito (3.4 km north El Mayor); Río Colorado at 6.4 km downstream the junction with Río Hardy, at Pongo de Abajo, 24.1 km south El Mayor, and 40.2 km above the mouth (Follett 1960: 227); Río Tijuana (3.2 km E Tijuana); a stream 23 km SE Tecate *ca.* Valle de

Las Palmas (CAS-119067, 119246); Ojos Negros 42 km E Ensenada (CAS-119247); Arroyo Guadalupe (= La Misión) at valley of Santa Rosa and town of La Misión, and Arroyo San Simón S San Quintín (Follett 1960: 227). Baja California Sur: Arroyo at Santiago and Arroyo San José del Cabo (Follett 1960: 227); Ojo de Agua de La Rosita at San Antonio, Ojo de Agua at San Bartolo, Arroyo La Tinaja [= El Túnel, Caduaño), and Presa (dam) Juárez *ca.* Todos Santos (Contreras-Balderas and Escalante-Cavazos 1984: 113).

Recent records. Baja California: Arroyo Alamar at Cañón del Padre; irrigation channel at Ejido Sinaloa (Varela *et al.* 2002: 162); mouth of Arroyo Cantamar (= El Médano); mouth of Arroyo El Descanso; mouth of Arroyo La Misión, La Misión town; Rancho Santa Rosa; Rancho Korodaki; Arroyo San Miguel; stream between Piedras Gordas and Las Minas; Emilio López Zamora dam; Arroyo San Carlos at Agua Caliente and Las Hamacas; streams of Las Animas, Santo Tomás, Seco [ca. Colonet], San Telmo, Santo Domingo (mouth) and Rancho El Divisadero; Arroyo El Rosario (lower part). Baja California Sur: Arroyo La Tinaja *ca.* Miraflores and Arroyo Boca de la Sierra at the base of the San Bernardino canyon (cf. Ruiz-Campos *et al.* 2002: 150).

Comments: This livebearer fish was introduced in northwestern Mexico for the control of mosquito, becoming an invasive species due to its high tolerance and competitive capacity to extreme environmental factors. There are two sources of distribution of mosquito fish in the Baja California Peninsula, one in the northwestern (Ruiz-Campos *et al.* 2000: 77) and the second at south of La Paz (Ruiz-Campos *et al.* 2002: 151). In northwestern Baja California is considered a current competitor of the native threespine stickleback *Gasterosteus aculeatus*, in the coastal streams of El Descanso, Santo Domingo and El Rosario (Ruiz-Campos *et al.* 2000: 77).

Poecilia latipinna (LeSueur, 1821)

Common name: Sailfin Molly / topote velo negro.

Native range: Atlantic and Gulf of Mexico coastal drainages, from Cape Fear drainage, North Carolina, to Veracruz, Mexico (Fuller *et al.* 1999: 309).

Previous records. Baja California: Río Hardy and Río Colorado (Hendrickson and Varela-Romero 1989: 480). Baja California Sur: None.

Recent records. Baja California: Río Hardy at campo Mosqueda, Río Colorado at Ejido Yucumuri, irrigation channel between Ejido Nayarit and Sonora (Varela-Romero *et al.*, 2002: 162), Río El Mayor at Campo Sonora, and Laguna Salada at El Paraíso fishery camp; Baja California Sur: None.

Comments: The sailfin molly is one of many exotic fishes that have been introduced in the waters of the lower Colorado River of California and Arizona (Dill and Cordone 1997: 124) and dispersed into the Mexican part of the basin. In the Ciénaga de Santa Clara (Sonora) this fish competes with endangered desert pupfish (*Cyprinodon macularius*) for space and food (Varela-Romero *et al.* 2002: 161).

Poecilia reticulata Peters, 1859

Common name: Guppy / gupi.

Native range: West Indies and northern South America, from west Venezuela to Guyana Guyana (Fuller *et al.* 1999: 312).

Previous records. Baja California: None. Baja California Sur: Presa (dam) Juárez at Todos Santos (UANL-2569 [303]) (Contreras-Balderas and Escalante-Cavazos 1984: 114).

Recent records. Baja California: Arroyo Cataviña (near Cataviña); and Arroyo Santa Gertrudis at Misión de Santa Gertrudis. Baja California Sur: Arroyo San José del Cabo; Arroyo Las Pocitas (two localities: Pozas del Vado and Rancho El Caracol); Arroyo San Pedro (seven localities: San Basilio, Pozo del Iritú, Rancho Merecuaco, Rancho Los Arados, Rancho El Caporal, and San Pedro de La Presa); Arroyo Bebelamas [three localities: Poza Honda (Rancho San Lucas), Rancho El Frijolito and Rancho San Antonio de la Montaña]; Arroyo San Luis (three localities: Misión de San Luis Gonzaga, Presa Higuajil and Rancho Las Cuedas); Arroyo La Zorra near Rancho Viejo; Arroyo San Javier at Misión de San (Francisco) Javier; Arroyo Comondú (two localities: San Miguel de Comondú and San José de Comondú); Arroyo La Purísima (seven localities: La Purísima, near San Gregorio estuary, San Isidro, El Pilón, Carambuche, La Purísima-San Juanico road, and Ojo de Agua); Arroyo La Purísima Vieja at Paso Hondo; Oasis La Purísima Vieja; Río Mulegé (dam); Arroyo Boca de Magdalena at San José de Magdalena; Arroyo San Joaquín (three localities: San Joaquín, El Sauzal and San Zacarías); Arroyo San Ignacio [eight localities: Oasis San Ignacio (two localities: spring and dam), Rancho El Tizón, Lake Side, San Lino, Poza Larga, Laguna Roberts, San Zacarías and Rancho San Sabas]; and San Gregorio stream at Sierra San Francisco.

Comments: It is the most invasive exotic fish in the freshwater bodies in the central and southern Baja California Peninsula, from Arroyo Cataviña (Baja California) to Arroyo San José del Cabo (Baja California Sur). From its first detection in 1977 at the tip of the Peninsula in Arroyo San José del Cabo (Ruiz-Campos and Contreras-Balderas 1987: 112), its dispersal to other inland waters has been enough quick and favored by the stocking via anthropogenic. The presence of the guppy in very remote sites of the Sierra de San Francisco (Rancho San Gregorio) was previously reported by Ruiz-Campos *et al.* (2002: 151).

Xiphophorus hellerii Heckel, 1848

Common name: Green Swordtail / cola de espada.

Native range: Middle America from Río Nantla, Veracruz (Mexico), to northwestern Honduras (Page and Burr 1991: 234; Fuller *et al.* 1999: 316).

Previous records: None.

Recent records. Baja California: None. Baja California Sur: Arroyo San Pedro at San Basilio and San Pedro de la Presa; Arroyo San Ignacio at the spring, El Tizón, bridge, Poza Larga, San Lino (front to Rice and Beans), Paso Los Pinos [between Los Corralitos and San Sabas] and San Sabas; and Arroyo San Joaquín at El Sauzal.

Comments: The green swordtail is syntopical with the native Baja California killifish *Fundulus lima* through the Río San Ignacio (except for locality of Los Corralitos) (Ruiz-Campos *et al.* 2006: 506) and Río San Pedro de La Presa (Ruiz-Campos *et al.* 2002: 151). The abundance of the green swordtail has been pretty decimated in the spring of San Ignacio due to the presence of other exotic competitor (redbelly tilapia) from 1996 (Ruiz-Campos *et al.* 2006: 508).

Family Cyprinidae

Cyprinus carpio Linnaeus, 1758

Common name: Common Carp / carpa común.

Native range: Eurasia (Page and Burr 1991: 64).

Previous records. Baja California: Río Colorado and its tributaries (Follett 1960: 227), as well as Laguna Salada (= Maquata) at La Playita (Ruiz-Campos and Contreras-Balderas 1987: 110). Baja California Sur: None.

Recent records. Baja California: Channel tributary to Laguna Salada; Río Colorado at Campo Gabriel and near the junction with Río Hardy. Baja California Sur: Río San Ignacio at the spring, bridge, Poza Larga, Los Corralitos and San Sabas (Ruiz-Campos *et al.* 2006: 506).

Comments: The presence of this Eurasian cyprinid in Baja California was first documented by Follett (1960: 227) for the Río Colorado and its tributaries in the Mexicali valley. In Baja California Sur, common carp was stocked into the San Ignacio oasis in 1973 to promote rural fish farming (Ruiz-Campos *et al.* 2002: 150). In both cases, the consumption of this fish is little frequent due to the bad flavor of its flesh and the feasibility to obtain fresh fish from the San Ignacio coastal lagoon. A specimen (UABC-1361) weighting 3.5 kg was caught using gillnet near the spring of the San Ignacio oasis on 26 October 2002. Two common morphs have been detected in the Peninsula of Baja California, the "mirror morph" in the Río San Ignacio and the "normally scaled morph" in the lower Colorado River basin (Ruiz-Campos 2012: 105).

Family Centrarchidae

Lepomis cyanellus Rafinesque, 1819

Common name: Green Sunfish / pez sol.

Native range: Native to Great Lakes, Hudson Bay, and Mississippi River basins from New York and Ontario to Minnesota and South Dakota, and south to Gulf of Mexico drainages, including the Rio Grande basin and northern Mexico (Page and Burr 1991: 267).

Previous records. Baja California: Río Tijuana, 3.2 km E Tijuana; a stream *ca.* Valle de Santa Rosa at 32.2 km S [sic] Ensenada (Follett 1960: 228); and Arroyo San Miguel (= Guadalupe or La Misión, CAS-19405). Baja California Sur: None.

Recent records. Baja California: Arroyo El Descanso (mouth and adjacent lagoon); mouth of Arroyo La Misión; Arroyo San Antonio de las Minas at Rancho Kodoraki and Rancho La Fortuna; Arroyo Doña Petra at Rancho Madrigal; Rancho Tierra Santa; Rancho Santa Rosa; Charco Escondido [Parque Nacional Constitución 1857]; Arroyo San Carlos at Rancho Las Hamacas and Rancho Alamitos; Arroyo Santo Tomás at Ejido Ajusco and La Bocana Santo Tomás; mouth of Arroyo San Telmo; and Arroyo Santo Domingo at Rancho El Divisadero. Baja California Sur: None.

Comments: The non-native presence of green sunfish in the streams of the Mediterranean region of Baja California was first reported by Follett (1960: 228) for the Santa Rosa valley (a tributary to Arroyo Guadalupe) on the basis of a personal communication via Dr. Carl L. Hubbs. This exotic centrarchid is a possible predator of the native threespine stickleback (*Gasterosteus aculeatus*) in the mouth of the Río El Descanso and its adjacent lagoon (Sánchez-Gonzáles *et al.* 2001: 192).

Family Cichlidae

Tilapia sp. cf. *zillii* (Gervais, 1848)

Common name: Redbelly Tilapia / tilapia panza roja.

Native range: Tropical and subtropical Africa, Near East; West Africa through Chad basin to Nile, Lake Albert, and Lake Turkana into Israel and Jordan Valley. This cichlid has been widely introduced by the man in many regions of the world, even the same African continent (Fuller *et al.* 1999: 451; Moyle 2002: 415).

Previous records: None.

Recent records. Baja California: Río El Mayor at Campo Sonora; irrigation channel between Ejido Nayarit and Ejido Sonora (Varela-Romero *et al.* 2002: 159); Presa (dam) Emilio López Zamora, and Arroyo San Juan de Dios at Rancho El Saucito. Baja California Sur: Oasis San Ignacio at spring, El Tizón, Lake Side, bridge (entry to San Ignacio town), San Lino (adjacent to Hotel Rice and Beans), Poza Larga, Rancho Los Estribos, Lagunita de Roberts, Rancho Los Corralitos, and Rancho San Sabas. Arroyo Cadejé at Cadejé (F. Reynoso-Mendoza, unpublished data); Arroyo Boca de Magdalena at San José de Magdalena; Arroyo San Martín at Rancho La Vinorama [Sierra de Guadalupe]; Arroyo La Purísima at San Isidro, El Pilón, bridge of Carambuche, La Purísima, Carambuche [= Cuba], Presa (dam) Carambuche, and Ojo de Agua; Oasis La Purísima Vieja; La Purísima Vieja at Paso Hondo; Arroyo Comondú at San Miguel de Comondú; Arroyo San Javier at Misión de San [Francisco] Javier; Higuajil dam; Poza Honda [Rancho San Lucas] and Rancho El Frijolito; Arroyo Bebelamas [Río Bramonas basin] at Rancho San Antonio de la Montaña; Arroyo San Luis at Misión de San Luis Gonzaga and Rancho Las Cuedas; Arroyo San Pedro at San Pedro de La Presa, San Basilio, Pozo del Iritú, Rancho Merecuaco, Rancho Los Arados and Rancho Tres Pozas; Arroyo La Soledad at El Quelele; and Arroyo San José del Cabo (Dr. Alejandro Maeda-Martínez, pers. comm.).

COMMENTS: Redbelly tilapia is one of the most invasive exotic fishes in the inland waters of the Peninsula of Baja California (Ruiz-Campos *et al.* 2002: 151, 2006: 506; Varela-Romero *et al.* 2002: 164) and southwestern U.S.A. (Dill and Cordone, 1997: 201). In the Lower Colorado River basin, this fish is the main cause of the decreasing in abundance and distribution of the desert pupfish populations, *Cyprinodon macularius* (Schoenherr 1988: 115; Varela-Romero *et al.* 2002: 164); likewise, in the oases of Baja California Sur has caused the extirpation of the endemic Baja California killifish (*Fundulus lima*) in the localities of Misión de San Javier (cuenca Río San Javier), Las Cuedas (cuenca Río San Luis), Poza Honda (cuenca Río Bebelamas), Misión de San Luis Gonzaga (Cuenca Río San Luis) and San Pedro de La Presa (cuenca Río San Pedro) (see Figure 2; Ruiz-Campos 2012: 129). The redbelly tiapia was first stocked into the at San Ignacio oasis in 1995 by a person from the adjacent town, but without considering the severe ecological effects that this event would generate a few years later. Previous to the introduction of redbelly tilapia, the Baja California killifish was the dominant fish in the spring habitat with relative abundances between 70 and 97% (Alaníz-García 1995: 22); however ten years later, this situation was reverted to favor the redbelly tilapia, which exhibit relative abundances as high as 84–94% (Ruiz-Campos *et al.* 2008: 29).

4. GENERAL CONSIDERATIONS

The invasion of non-native aquatic species to new areas should be considered a process that involves three steps: initial dispersal, establishment, and radiation (Elton 1958). In each step exists selective pressures operating on the survival of organisms in order to diminish of successive way the total pool of species and increase the success of invasion (Williamson 1996). In this sense, several hypotheses have been proposed to explain the patterns of invasion by exotic species in the aquatic ecosystems. The first hypothesis (human activity) makes reference to the steps of initial invasion, establishment and radiation; while the second hypothesis (biotic acceptance) predicts that the establishment of nonnative species will be higher for rich areas in native species, where the abiotic conditions are favorable for both; and finally, the third hypothesis (biotic resistance) explains that the success of the invasion decreases in relation to the species richness in the community (cf. Elton 1958, Gido and Brown 1999, Leprieur *et al.* 2008) and the time of accumulation of species.

One of the aquatic ecosystems of the northwestern Mexico more strongly impacted by the introduction of exotic fishes is the lower Rio Colorado basin, where at least 23 species have been recorded (Ruiz-Campos *et al.*, 2012). This high number of exotic fishes is resulting of the accumulation of species by almost a century through the active dispersal from the reservoirs and irrigation channels of Arizona. Significant fluctuations in the base flow of the Colorado River has generated the extinction of fish species associated to conditions of high levels of current flows (discharge) such as the endemics, *Xyrauchen texanus, Gila elegans* and *Ptychocheilus lucius* (Rinne and Minckley 1991; Varela-Romero and Hendrickson 2009) as well as the establishment of exotic fishes tolerant to these hydrological changes such as red shiner, sailfin molly, mosquito fish and redbelly tilapia (Varela-Romero *et al.* 2002), all of them have dispersed into the agriculture irrigation channels in the Mexicali valley. In this same basin, but in spring and wetland habitats, the abundance of the desert pupfish *Cyprinodon macularius* has been dramatically decreased in those historic distribution localities (Follett 1960, Hendrickson and Varela-Romero 1989, Varela-Romero *et al.* 2002, Miller *et al.* 2005), mainly by competition with redbelly tilapia and sailfin molly interaction (Varela-Romero *et al.* 2002).

Based on the niche theory (Chase and Leibold 2003), two species occurring on the same space and time cannot have identical realized niches because one would be excluding the other. Exotic species with ample potential niches such as occur with invasive species, which trend to become dominant forms when introduced in systems containing species with specialized ecological niches. Thus, significant alterations in the habitat conditions of the native species will promote the expression of potential niches of the exotic species with high environmental tolerance. The oases of Baja California Sur, characterized by the low diversity of native fish fauna, contain endemic fishes as the Baja California killifish (*Fundulus lima*) and Baja freshwater clingfish (*Gobiesox juniperoserrai*), as well as forms of marine or peripheral derivation such as *Awaous banana*, *Eleotris picta*, *Gobiomorus maculatus*, *Dormitator latifrons*, and *Agonostomus monticola* (Follett 1960, Ruiz-Campos *et al.* 2002, Ruiz-Campos 2010).

This native fish taxocenosis has been strongly modified and decimated by the introduction of exotic fishes, especially of redbelly tilapia. In Baja California Sur, the first introduction of redbelly tilapia occurred in 1986 for the Río Purísima basin (Ruiz-Campos *et al.* 2002). This exotic species was repeatedly stocked into others basins causing the extirpation of the endemic killifish and peripheral fishes in the oases of San Javier, San Pedro de la Presa, Las Cuedas, Paso Iritú, San Luis Gonzaga (Ruiz-Campos 2012), and most recently at Poza Honda (Ruiz-Campos, obs. pers.).

In spite of that the eradication of invasive exotic fishes in the oases of the Baja California Peninsula is virtually impossible, one strategy that might reduce and mitigate the impacts of the exotic species on the natives is the implementation of a permanent program of removing for exotic fishes using active and passive capture techniques.

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APPENDIX 1

Examined material of exotic fishes from the Peninsula of Baja California, Mexico. The collecting sites for voucher specimens followed by catalog numbers and number of specimens in square brackets.

Poecilia reticulata

Baja California: Arroyo *ca.* Cataviña (UABC-726 [42], 877 [75]), La Bocana at Cataviña (UABC-1350 [3]). Baja California Sur: Río San José del Cabo at San José del Cabo (UABC-754 [1]); Presa (dam) Juárez at Todos Santos (UANL-2569 [303]); Arroyo Las Pocitas at Poza del Vado (UABC-1563 [65], 1575 [20]) and Rancho El Caracol (UABC-1564 [11], 1576 [24], 1577 [50], 1582 [99], 1592 [9]); Arroyo San Pedro at San Basilio (UABC-780 [39]), Pozo del Iritú [Encinas] (UABC-784 [69], 1574 [14]), Rancho Merecuaco (UABC-793 [50]), Rancho Los Arados (UABC-1583 [8]), San Pedro de La Presa (UABC-1317 [42], 1321 [31], 1419 [1], 1485 [6]); Arroyo El Caporal at Rancho El Caporal (UBC-1307 [50]); Arroyo Bebelamas at Poza Honda [Rancho San Lucas] (UABC-746 [37], 2359 [62]), Rancho El Frijolito (UABC-749 [71], 2357 [42]) and San Antonio de la Montaña (UABC-1311 [18]); Arroyo San Luis [dam] at Misión de San Luis Gonzaga (UABC-752 [196], 757 [23], 1579 [19]), Presa Higuajil (UABC-742 [2]) and Rancho Las Cuedas (UABC-1301 [62], 1578 [30], 1586 [34]); Arroyo La Zorra *ca.* Rancho Viejo (UABC-1483 [117]); Arroyo San Javier [dam] at Misión de San [Francisco] San Javier (UABC-822 [170], 823 [61], 912 [7], 2354 [24], 2355 [6]); Arroyo Comondú at San Miguel de Comondú (UABC-765 [339]) and San José de Comondú (UABC-763 [149], 764 [162]); Arroyo La Purísima *ca.* San Gregorio estuary (UABC-2158 [2], San Isidro (UABC-727 [5], La Purísima [dam and bridge] (UABC-761 [48], 827 [1]), El Pilón (UABC-1501 [1]), Carambuche [Cuba] (UABC-760 [16], 828 [1]), 1529 [1]), Presa (dam) Carambuche (UABC-761 [48], 827 [1]), Puente (bridge) Carambuche (UABC-1533 [12]), and Ojo de Agua (UABC-1467 [25], 1580 [22]); La Purísima Vieja at Paso Hondo (UABC-1466 [7], 1554 [19]); Río Mulegé [dam] (UABC-146 [83], 907 [7]); Arroyo Boca de Magdalena at San José de Magdalena (UABC-737 [18], 908 [26]); Arroyo San Joaquín at San Joaquín (UABC-733 [81], El Sauzal (UABC-734 [11], 1474 [76]) and San Zacarías (UABC-075 [36]); Oasis San Ignacio at spring (UABC-080 [51], 936 [26], 1306 [58], 2129 [2]), El Tizón (UABC-1536 [7]), Lake Side (UABC-1437 [39], 1496 [2]), San Lino at front of Hotel Rice and Beans (UABC-1527 19]), Poza Larga (UABC-1314 [18], 1447 [76], 1457 [40], 1503 [2], 2133 [1]), Laguna Roberts (UABC-1497 [32]), San Sabas (UABC-1456 [40], 1502 [4]); Arroyo San Gregorio at Sierra San Francisco (UABC-725 [138]); and Arroyo Santa Gertrudis at Santa Gertrudis Mission.

Gambusia affinis

Baja California: an unnamed stream *ca.* Valle de Las Palmas (CAS-119067, 119246) and Ojos Negros (CAS-119247), Arroyo Alamar at Cañón del Padre (UABC-1351 [1]); mouth of Arroyo El Descanso (UABC-409 [14], 411 [710]) and its adjacent lagoon (UABC-435 [7], 481 [6], 996 [27]); Arroyo La Misión (mouth: UABC-216 [2], 487 [7], UANL-13720 [8]; town: UABC-050 [3], 073 [9]) and tributaries at Rancho Santa Rosa UABC-376 [65], 875 [14]) and Rancho Korodaki [= fall of Agua Caliente] (UABC-1297 [29]); Arroyo San Miguel [= El Carmen] (UABC-201 [10], 488 [99]); unnamed stream between Piedras Gordas and Las Minas (UABC-1356 [3]); Presa (dam) Emilio López Zamora (UABC-1593 [1]); Arroyo San Carlos at ranches of Las Hamacas (UABC-932 [7]) and Agua Caliente [hot spring] (UABC-954 [3]); Arroyo Las Animas (UABC-1360 [54]); Arroyo Santo Tomás [Ejido Ajusco] (UABC-605 [2]), Arroyo Seco [ca. Colonet] (UABC-317 [56]), Arroyo San Telmo (UABC-169 [61], 312 [315], 471 [26]), Arroyo Santo Domingo (mouth, UABC-166 [1], 310 [9]; and Rancho El Divisadero, UABC-455 [112], 592 [30], 1026 [12]); Arroyo El Rosario (UABC-160 [2], 162 [30], 309 [14], 320 [56], 458 [130], 462 [12], 584 [32], 892 [3], 959 [[1], 1024 [7], 2094 [13], 2096 [15], 2100 [1], 2109 [1]); Río Colorado at tributary channel of Laguna Salada (USON-174 [1]); Río Hardy at campo Mosqueda (USON-191 [114]); Río Colorado at Ejido Yucumuri [Campo Escondido] (USON-196 [347]; Río Hardy at Campo Mosqueda [La Cabaña] (USON-204 [1098]); La Laguna Salada at El Paraíso fishery camp (USON-209 [27]; a channel effluent to agricultural lands at S Ejido Nayarit (USON-214 [28]). Baja California Sur: Ojo de Agua de La Rosita (UANL-2543 [44]), Ojo de Agua de San Bartolo (UANL-2547 [383]), Arroyo La Tinaja *ca.* Miraflores (UANL-2553 [49], UABC-751 [88]) and Arroyo Boca de la Sierra (UABC-767 [29]); Presa (dam) Juárez *ca.* Todos Santos (UANL-2568 [75]).

Poecilia latipinna

Baja California: Río El Mayor at Campo Sonora (UABC-100 [46], 135 [7], 136 [15]); Río Hardy at campo Mosqueda (USON-192 [224]; Río Hardy Campo Mosqueda at La Cabaña (USON-205 [1941]); Río Colorado at Ejido Yucumuri (USON-197 [13], 953 [57]); La Laguna Salada at El Paraíso fishery camp (USON-210 [1]);]; and channel effluent to agricultural lands at S Ejido Nayarit (USON-215 [1802], 921 [9], 929 [19], 966 [45], 989 [68]).

Cyprinus carpio

Baja California: Channel effluent to Laguna Salada (UABC-117 [8]), Río Colorado *ca.* 60 m (UABC-222 [1]), 100 m (UABC-108 [1]), and 800 m (UABC-414 [2]) before the junction with Río Hardy; and Río Colorado at Campo Gabriel

(UABC-951 [2]). BAJA CALIFORNIA SUR: Río San Ignacio at Ojo de Agua (UABC-076 [1], 721 [1], 1361 [1]; Contreras-Balderas, 1999: 33), bridge of Río San Ignacio (UABC-1449 [2], 1537 [2]), Poza Larga (UABC-1300 [3], 1428 [23], 1506 [11], 1538 [3], 1608 [15]), Los Corralitos (UABC-1453 [2], 1551 [2]), 2121 [5], and San Sabas (UABC-1550 [1]).

Lepomis cyanellus

BAJA CALIFORNIA: Arroyo El Descanso (adjacent lagoon, UABC-177 [1]), mouth of Arroyo La Misión (UABC-865 [1]); Arroyo San Antonio de las Minas at Rancho Kodoraki (G. Ruiz-Campos, pers. obs..) and at Rancho La Fortuna (UABC-2051 [25]), Arroyo Doña Petra at Rancho Madrigal (UABC-1491 [1]), Rancho Tierra Santa (UABC-183 [16], 665 [33]); Rancho Santa Rosa (UABC-377 [4], 876 [1]); Charco Escondido [Parque Nacional Constitución 1857] (UABC-1488 [1]), Arroyo Santo Tomás at Ejido Ajusco (UABC-224 [2]) and La Bocana Santo Tomás (UABC-452 [1]); and mouth of Arroyo San Telmo (UABC-311 [6]).

Tilapia sp. cf. *zillii*

BAJA CALIFORNIA: Río El Mayor at Campo Sonora (UABC-109 [17], 119 [1]); Presa (dam) Emilio López Zamora (UABC-1037); Arroyo San Juan de Dios at El Saucito (UABC- 1653 [188]); and irrigation channel betwen Ejido Nayarit and Ejido Sonora (USON-990 [7]). BAJA CALIFORNIA SUR: Arroyo Las Pocitas at Rancho El Cantil (UABC-2363 [3], Arroyo La Soledad at Rancho El Quelele (UABC-2246[6]), Arroyo San Pedro at San Pedro de La Presa (UABC-1322 [5], 1329 [1], 1423 [224]), San Basilio (UABC-783 [18], 1424 [12]), Pozo del Iritú (UABC-788 [13], 1562 [11], 1573 [16]), Rancho Merecuaco (UABC-792 [4]), Rancho Los Arados (UABC-1572 [16], 1584 [23]) and Rancho Tres Pozas (UABC-795 [3]); Arroyo San Luis at Misión de San Luis Gonzaga (UABC-739 [13], 1571 [15], 1585 [23]) and Rancho Las Cuedas (UABC-744 [3], 750 [5], 1303 [39], 1570 [13], 1587 [17]); Arroyo Bebelamas [Bramonas basin] at Rancho San Antonio de la Montaña (UABC-1310 [60]), Poza Honda [Rancho San Lucas] (UABC-747 [126], 2358 [13]) and Rancho El Frijolito (UABC-748 [1], 2360 [81]); Presa (dam) Higuajil (UABC-741 [18]); Arroyo San Javier at Misión de San [Francisco] Javier (UABC-819 [3], 820 [73], 821 [22], 911[13], 1545 [92], 2356 [4]); Arroyo Comondú at San Miguel de Comondú (UABC-766 [1]); La Purísima Vieja at Paso Hondo (UABC-1546 [39], 1558 [57]), Oasis La Purísima Vieja (UABC-1547 [22], 1557 [5]), Arroyo La Purísima *ca.* San Gregorio estuary (UABC-2157 [14]), San Isidro (UABC-728 [2]), El Pilón (UABC-1441 [30], 1482 [3], 1511 [277]), bridge of Carambuche (UABC-1531 [8]), La Purísima (UABC-762 [90], 825 [34]), Carambuche [= Cuba] (UABC-759 [38], 826 [8], 1299 [2], 1528 [2]), Presa (dam) Carambuche (UABC-1302 [15], 1408 [39], 1415 [33], 1440 [15], 1523 [43]), and Ojo de Agua (UABC-1406 [11], 1410 [27], 1412 [7], 1420 [41], 1427 [2], 1429 [10], 1439 [3], 1510 [36]), 1548 [1]); Arroyo San Martín at Rancho La Vinorama [Sierra de Guadalupe] (UABC-738 [1]); Oasis San Ignacio at spring (UABC-942 [10], 1304 [30], 1469 [149], 1495 [127], 2091 [28]), El Tizón (UABC-1442 [78], 1534 [21]), Lake Side (UABC-1459 [86], 1521 [14]), San Ignacio [bridge of] (UABC-1443 [1], 1444 [4]), San Lino [front of Hotel Rice and Beans] (UABC-1525 [18], Poza Larga (UABC-1494 [1], 1509 [82], 1520 [14], 1581 [11], 2130 [10], 2131 [73], 2132 [25]), Rancho Los Estribos (UABC-1411 [30], 1414 [26]), Lagunita de Roberts (UABC-1519 [19]), Rancho Los Corralitos (UABC-1454 [2], 1455 [30], 1507 [4], 1552 [1], 2085 [63], 2086 [81], 2087 [71]), Rancho Los Pinos (UABC-2084 [44], 2088 [26], 2089 [23], 2090 [51]) and Rancho San Sabas (UABC-1493 [2], 1508 [15], 1522 [4], 1549 [1]).

APPENDIX 2

Toponomy and geographical coordinates of the collecting sites for exotic fish species in the Peninsula of Baja California, Mexico.

Baja California:

1. Bocana Arroyo Cantamar (= Médano). 32°13'44.2" N, 116°55'21.5" W.
2. Bocana Arroyo El Descanso (= La Posta). 32°12'09.3" N, 116°54'47.8" W.
3. Bocana Arroyo La Misión (= Guadalupe). 32°05'32.0" N, 116°52'50.0" W.
4. Poblado La Misión. 32° 5'45" N; 116° 51'30" W.
5. Arroyo Guadalupe at Rancho Santa Rosa (= El Salto). 32°13'43.9" N, 116°55'21.6" W.
6. Arroyo Guadalupe at Rancho Tierra Santa (Ejido El Porvenir). 32°05'00.0" N, 116°37'00.0" W.
7. Bocana Arroyo San Miguel (= El Carmen), Ensenada. 31°54'05.8" N, 116°43'48.4" W.
8. Arroyo Las Ánimas at Ejido Uruapan. 31°37'00.0" N, 116°26'00.0" W.
9. Bocana Arroyo Santo Tomás. 31°32’12.9" N, 116°39'28.0" W.
10. Arroyo Santo Tomás at Ejido Ajusco. 31°35'00.0" N, 116°28'00.0" W.
11. Bocana Arroyo San Vicente. 31°15'54.3" N, 116°22'51.7" W.
12. Bocana Arroyo El Salado (*ca.* Loma Linda). 31°06'35.5" N, 116°17'50.4" W.
13. Arroyo Seco *ca.* Colonet. 31°05'56.1" N, 116°10'58.9" W.
14. Bocana Arroyo San Rafael *ca.* Punta Colonet. 30°58'08.1" N, 116°16'29.8" W.
15. Bocana Arroyo San Telmo *ca.* Punta San Telmo. 30°56'29.5" N, 116°14'57.6" W.
16. Bocana Arroyo Santo Domingo *ca.* San Ramón. 30°42'53.6" N, 116°02'31.6" W.
17. Arroyo Santo Domingo at Rancho El Divisadero. 30°46'21.4" N, 115°54'19.5" W.

18. Bocana Arroyo San Simón (*ca.* Ejido El Papalote). 30°27'04.1" N, 115°55'36.3" W.
19. Bocana Arroyo San Simón (1 km above Hotel La Pinta). 30°24'24.1" N, 115°54'24.3" W.
20. Bocana Arroyo El Rosario. 30°02'32.5" N, 115°47'15.6" W.
21. Arroyo Neji *ca.* Ejido Neji. 32°23'00.0" N, 116°19'00.0" W.
22. Laguna Hanson, Sierra Juárez. 32°02'00.0" N, 115°54'00.0" W.
23. Arroyo San Carlos at Rancho Alamitos. 31°46'00.0" N, 116°31'00.0" W.
24. Bocana Arroyo San Fernando, Ensenada. 29°43'33.7" N, 115°38'49.6" W.
25. Arroyo Cataviña *ca.* Cataviña. 29°52'4.5776" N, 114°56'59.989" W.
26. Arroyo Alamar, Cuenca del Río Tijuana. 32°31'27.5”N, 116°54'46.8”W.
27. Arroyo (unnamed) between Piedras Gordas and Las Minas. 31°55'46.1”N, 116°27'04.7”W.
28. Arroyo San Carlos at Rancho Las Hamacas. 31°47'51.6" N, 116°30'02.4" W.
29. Arroyo San Carlos at Balneario [swimming pool] Agua Caliente. 31°46'0”N, 116°31'0”W.
30. Presa (dam) Emilio López Zamora. 31°54'08.5" N, 116°35'37.8" W.
31. Arroyo Guadalupe at Rancho Korodaki. 32° 06'15.8" N, 116° 27'03.4" W.
32. Charco Escondido, Parque Constitución 1857. 32°00'10.8" N, 115°56'50.52"W.
33. Arroyo San Antonio de las Minas, San Antonio de las Minas. 21°58’32.2"N 116°37’55.4"W.
34. Río Colorado *ca.* junction with Río Hardy. 32° 6'0" N; 115° 13'45" W.
35. Río Hardy *ca.* junction with Río Colorado. 32° 6'0" N; 115° 14'15" W.
36. Channel effluent to Laguna Salada. 31° 58'N; 115° 13'W.
37. Río El Mayor at Campo Sonora. 32° 0'4" N; 115° 18'0" W.
38. Represa (dam) at Rancho Tierra Santa, Ejido El Porvenir. 32°5'0" N; 116°37'0" W.
39. Río Pescadores at Rancho Caimán. 32°13'30"N, 115°11'30”W.
40. Canal Cerro Prieto o Solfatara (= Pacífico). 32°30'N, 115°27'W.
41. La Playita, northwestern edge of Laguna Salada. 32°31'0" N, 115°45'0" W.
42. Arroyo San Juan de Dios at El Saucito. 30° 06'51.8" N, 115° 21'18.9" W.
43. Arroyo Cañón de Doña Petra at Rancho Madrigal. 31°55'20.9"N, 116°36'13.4"W.
44. Río Colorado, kilometer num. 76, Mexicali-San Felipe freeway, under the bridge. 31°56'N, 115°12'W.
45. Río Hardy at campo Mosqueda. 32°5'N, 115°12'W.
46. Río Hardy at La Cabaña *ca.* Campo Mosqueda,. 32°8'N, 115°11'W.
47. La Laguna Salada at El Paraíso fishery camp, km. num. 23, Mexicali-Tijuana freeway. 32°38'N, 115°39'W.
48. Río Colorado at Ejido Yucumuri (Campo Escondido), km. num. 67, Mexicali-San Felipe freeway. 32°5'N, 115°10'W.

49. Irrigation channel between Ejido Nayarit and Ejido Sonora. 32°17'41.3"N., 115° 15'20.5"W.
50. Arroyo Santa Gertrudis at Mission of Santa Gertrudis

Baja California Sur:

1. Arroyo [Ojo de Agua] at San José del Cabo. 23°03'32.0" N, 109°41'28.8" W.
2. Arroyo San Venancio at San Venancio. 23°16'48.6'N, 110°02'7.3" W.
3. Arroyo La Tinaja (El Aguajito) *ca.* Miraflores. 23°21'59.4" N, 109°45'19.2" W.
4. Arroyo Boca de La Sierra on the basis of San Bernardino canyon *ca.* Miraflores. 23°23'10.6" N, 109°49’11.7" W.
5. Presa Juárez *ca.* Todos Santos. 23°32'44.4" N, 110°08'44.1" W.
6. Ojo de Agua de San Bartolo. 23°44'11.0" N, 109°50'25.0" W.
7. Ojo de Agua de La Rosita at San Antonio. 23°48'20.1"N, 110°03'41" W.
8. Arroyo Las Pocitas at Pocitas del Vado. 24°23'N, 111°06'W.
9. Arroyo Las Pocitas at Rancho El Caracol. 24°32'N, 111°01'W.
10. Arroyo Las Pocitas at Rancho El Cantil. 24°35'29.4" N, 110°59'32.9" W.
11. Arroyo La Soledad at El Quelele. 24 48'37.5" N, 110 50'32.5" N.
12. Arroyo Los Dolores at Misión de Santa Dolores. 25 04'27.1" N, 110°51'40.1" W.
13. Arroyo La Presa at La Presa de Toris [= Toris de La Presa]. 24°54'N, 111°02'W.
14. Arroyo San Pedro at Pozo del Iritú [= Rancho Encinas]. 24°46'55.0" N, 111°09'02.4" W.
15. Arroyo San Pedro at Rancho Los Arados. 24°47'06.5" N, 111°11'07.2" W.
16. Arroyo San Pedro at Rancho Merecuaco. 24°48'25.2" N, 111°09'03.6" W.
17. Arroyo San Pedro at Rancho Tres Pozas, entre El Carracito [sic] y El Ciruelo. 24°48'58.1" N, 111°07'33.0" W.
18. Arroyo San Pedro at San Basilio, antes de la confluencia con Arroyo La Presa. 24°50'13.1" N, 111°04'37.4" W.
19. Arroyo San Pedro at San Pedro de La Presa. 24°51'N, 110°59'W.
20. Arroyo San Pedro at Rancho El Caporal. 24 49'47.5" N, 111 13'09.5" W.
21. Arroyo San Luis at Rancho Las Cuedas. 24°53'59.4" N, 111°14'58.7" W.
22. Arroyo San Luis at Misión de San Luis Gonzaga. 24°54'34.8" N, 111°17'21.5"W.
23. Arroyo Bebelamas at Poza de la Caguama [Rancho San Antonio de la Montaña]. 24 57'33.8" N, 111 19'21.1" W.
24. Arroyo Bebelamas at Rancho El Frijolito [= El Frijol]. 24°57'29.0" N, 111°19'06.0" W.
25. Arroyo Bebelamas at Rancho San Lucas (Poza Honda). 24°57'44.6" N, 111°20'17.9" W.

26. Arroyo San Luis at Presa Higuajil. 24°58'22.7" N, 111°23'37.2" W.
27. Arroyo San Javier (dam and spring) at Misión de San [Francisco] Javier. 25°52'07.0" N, 111°32'49.0" W.
28. Arroyo La Zorra, 2 km above Rancho Las Parras). 25°57'20.2" N, 111°31'06.8" W.
29. Arroyo San Javier at Rancho Viejo. 25°56'30.3" N, 111°32'05.1" W.
30. Arroyo San Javier at El Carrizal (between Los Hornos y Chula Vista ranches). 25°52'31.0" N, 111°32'38.5" W.
31. Arroyo La Tasajera between Canipolé and Uña de Gato, Loreto. 26°20'46.1" N, 111°47'12.5" W. [dry strambed].
32. Arroyo Comondú at San Miguel de Comondú. 26°01'57.6" N, 111°49'58.3" W.
33. Arroyo Comondú at San José de Comondú. 26°03'32.4" N, 111°49'29.3" W.
34. Arroyo La Purísima at San Isidro. 26°12'29.4" N, 112°02'26.6" W.
35. Arroyo La Purísima at the ford of the La Purísima-San Juanico road. 26°09'32.2"N, 112°07'42.2" W
36. Arroyo La Purísima at La Purísima. 26°10'58.7" N, 112°05'18.5" W.
37. Arroyo La Purísima at Carambuche [= Cuba]. 26°12'58.6" N, 112°01'12.9" W.
38. Arroyo La Purísima at Presa (dam) Carambuche. 26°14’19.8" N, 112°00'03.6" W.
39. Arroyo La Purísima at Ojo de Agua. 26°19'24.2" N, 111°59'09.7" W.
40. Arroyo La Purísima Vieja at La Purísima Vieja. 26°18'39.9" N, 112°09'43.8" W.
41. Arroyo La Purísma Vieja at Paso Hondo. 26°20'08.2" N, 112°09'48.2" W.
42. Arroyo San Martín at Rancho La Vinorama, between El Tule and Martín ranches. 26°38'14" N, 112°17'27" W.
43. Río Mulegé between the bridge and the mouth. 26°53'54'N, 111°57'58" W.
44. Ojo de Agua del Río Mulegé (above the dam). 25°53'12.5" N, 111°59'12.1" W.
45. Arroyo Boca de Magdalena at San José de Magdalena. 27°04'08.7" N, 112°12'07.9" W.
46. Oasis San Ignacio at spring. 27°17'48.3" N, 112°52'55.1" W.
47. Arroyo San Ignacio at El Tizón. 27°17'53.2" N, 112°53'12.3" W.
48. Arroyo San Ignacio at Lake Side. 27°17'56.0" N, 112°53'39.0" W.
49. Arroyo San Ignacio at bridge of access to the town of San Ignacio. 27°17'51.3" N, 112°53'50.8" W.
50. Arroyo San Ignacio at San Lino [front to Hotel Rice and Beans]. 27°17'52.1" N, 112°54'17.6" W.
51. Arroyo San Ignacio at Poza Larga. 27°16'26.1" N, 112°54'46.5" W.
52. Arroyo San Ignacio at Rancho Los Estribos. 27°15'40.2" N, 112°55'40.9" W.
53. Arroyo Sam Ignacio en Poza Roberts. 27°14'43.6" N, 112°57'31.6" W.
54. Arroyo San Ignacio at Los Corralitos. 27°13'01.9" N, 112°59'16.9" W.
55. Arroyo San Ignacio at Paso Los Pinos. 27°12'37.3" N, 112°59'54.8" W.

56. Arroyo San Ignacio at San Sabas. 27°11'51.8" N, 113°00'09.3" W.
57. Arroyo San Joaquín at San Zacarías. 27°08'N, 112°54' W.
58. Arroyo San Joaquín at El Sauzal. 27°10'N, 112°52' W.
59. Arroyo San Joaquín at San Joaquín. 27°11'N, 112°51' W.
60. Arroyo San Gregorio at Rancho San Gregorio, Sierra San Francisco. 27°40'35.5" N, 113°01'02.8" W.

POLLINATION BIOLOGY OF SONORAN DESERT SUCCULENTS AND THEIR POLLINATORS: EVOLUTION AND CO-EVOLUTION AT A BIOGEOGRAPHIC BOUNDARY

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The pollination biology of six species of Sonoran Desert columnar cacti and two species of paniculate agaves falls along a continuum from extreme specialization (as seen in the moth-pollinated *Pachycereus schottii*) to generalization involving bats, birds, and insects in two cacti (*Carnegiea gigantea*, *Stenocereus thurberi*) and one agave (*Agave subsimplex*). Two species (*Pachycereus pringlei*, *Agave angustifolia*) rely heavily on the nectar-feeding bat *Leptonycteris yerbabuenae* for pollination. Low pollinator reliability (which occurs most strongly in *Stenocereus eruca*) is thought to favor pollinator generalization in these plants, which are among the most charismatic species in this region. Unusual reproductive characteristics, including a trioecious breeding system in *P. pringlei*, the ability to use a different cactus species' pollen to set fruit in *S. thurberi*, and active pollination in *P. schottii*, occur in these species. Most of the vertebrate pollinators of these plants are migratory and have special conservation concerns. Continued reproductive success in these Sonoran Desert succulents depends strongly on habitat conservation both within and outside of this region.

1. INTRODUCTION

In the spring, the floral landscape of the Sonoran Desert is dominated by the color yellow. The yellow flowers of brittlebush and desert marigold stand out at ground level while among trees, the yellow flowers of whitethorn acacias, palo verdes, and mesquites predominate. To be sure, other colors such as the red flowers of ocotillo and lavender flowers of desert ironwood provide some relief in this sea of yellow, but yellow clearly is the color of choice for the flowers of many Sonoran Desert plants. Knowing that this habitat harbors one of the highest diversities of bees in the world makes it easy to understand why yellow is the preferred flower color. Bees are the most important pollinators of plants in this and many other habitats worldwide, and bee flowers are often yellow in color. But not all Sonoran Desert plants are bee-pollinated, and, as indicated above, not all of its plants produce yellow flowers. Hummingbirds, for example, are common in the Sonoran Desert and are the principal pollinators of plants with red tubular flowers such as species of ocotillo and the gracile columnar cactus *Stenocereus* (*Rathbunia*) *alamosensis*. Among night-blooming plants pollinated by moths or bats, white is the most common flower color.

Although relatively few Sonoran Desert plants are pollinated by birds and bats, these plants and their flowers are among the most charismatic and ecologically important members of this region. To many people familiar with this region, the strange and stately saguaro (*Carnegiea gigantea*), cardon (*Pachycereus pringlei*), and organ pipe (*Stenocereus thurberi*) cacti alone define the Sonoran Desert. In this chapter we review the pollination biology of these cacti and some of their close relatives as well as certain members of the Agavaceae, another group of succulent plants that often share pollinators with columnar cacti. Motivating questions that we address include: (1) to what extent do these plants depend on bats for pollination; how diverse are the pollination systems of Sonoran Desert columnar cacti and agaves; (2) what, if anything, is novel about the reproductive and pollination systems of these plants; and (3) how finely tuned or co-evolved are these plants and their pollinators? Before addressing these questions, we will briefly review the evolutionary history and biogeography of these plants and their chiropteran pollinators.

2. THE EVOLUTIONARY HISTORY AND BIOGEOGRAPHY OF SONORAN DESERT COLUMNAR CACTI, AGAVES, AND THEIR POLLINATORS

Located between latitudes 25° and 35° N in southwestern Arizona (and a small part of adjacent California), coastal Sonora, and most of Baja California, the Sonoran Desert lies at the northern boundary of the geographic ranges of vertebrate-pollinated columnar cacti and other arid-adapted succulents and their pollinators. The evolutionary origins of these organisms lie farther south in arid and semiarid regions of the Neotropics. Subfamily Cactoideae of the Cactaceae, for example, likely first evolved in the central Andes at least 30 million years ago (Arakaki *et al.* 2011). From there different tribes of Cactoideae migrated south (Trichocereeae, Notocacteae), east (Cereeae), and north (Hylocereeae, Leptocereeae, Cacteae, Pachycereeae) with two main lineages (Pachycereeae in Greater Mexico and the Browningieae-Cereeae-Trichocereeae [BCT] clade in South America) giving rise to the bulk of the 'giant' or columnar cacti (Wallace 2002, Yetman 2007). Of the approximately 130 currently recognized species of columnar cacti, at least 60 occur in Mexico and about 40 occur in Brazil. Most of these plants are pollinated by vertebrates.

Tribe Pachycereeae contains two currently recognized subtribes (Pachycereinae and Stenocereinae) and at least 10 of its genera and 70% of its species are primarily or exclusively bat-pollinated. Genera notable for their species richness in this tribe include *Stenocereus* (with 19+ species) in the Stenocereinae, and *Neobuxbaumia* (9+ species), *Pachycereus* (9 species, including two *Lophocereus*), and *Cephalocereus* (5 species) in the Pachycereinae; the monotypic genus *Carnegiea* (saguaro) also occurs in subtribe Pachycereinae (Yetman 2007). The closest relatives of saguaro, cardon, and organ pipe are thought to be *Neobuxbaumia mezcalaensis* of Puebla and Oaxaca, *Pachycereus grandis* of central Mexico, and *Stenocereus martinezii* of Sinaloa, respectively (Gibson and Horak 1978, Cota and Wallace 1997). Senita (or sinita), *Pachycereus schottii* (formerly *Lophocereus schottii*), is a moth-pollinated columnar that often co-occurs with the three larger species in much of the Sonoran Desert. Its closest relative is the hummingbird-pollinated *Pachycereus marginatus* of central Mexico (Hartmann *et al.* 2002). Hartmann *et al.* (2002) speculate that the shift from bat pollination to hummingbird and moth pollination in *P. marginatus* and *P. schottii*, respectively, represents a single evolutionary event (cf. two independent events). Selective pressures favoring these shifts have not yet been studied. To judge from its very low level of cytoplasmic and chloroplast DNA variation, *P. schottii* is a recently derived species (Hartmann *et al.* 2002). It may have evolved in southern Baja California where its highest genetic diversity occurs (Nason *et al.* 2002).

In contrast to the above estimates of species richness and taxonomy, Arias and Terrazas (2009) suggest that *Pachycereus* contains only five species (*P. grandis, P. pringlei, P. weberii, P. pecten-aboriginum*, and *P. tepamo*) and that *Lophocereus* should contain *P. marginatus* as well as *L. schottii*. Classification and phylogenetic relationships within tribe Pachycereinae are clearly still in a state of flux, and we will adhere to Yetman's (2007) treatment of these cacti in this chapter.

Molecular data suggest that the Agavaceae, which is narrowly defined here to include only New World taxa (Heywood *et al.* 2007), arose 21–26 mya (Good-Avila *et al.* 2006). *Yucca* (with about 49 species) and *Agave* (which in the broad sense includes *Manfreda*, *Polianthes*, and *Prochynanthes* contains about 210 species; *Agave sensu stricto* contains about 166 species) are the family's two largest genera. Good-Avila *et al.* (2006) suggest that the genus *Agave* (*sensu stricto*) evolved in Mexico in the Miocene (9–10 mya) and that it underwent two periods of rapid speciation 6–8 and 2.5–3 mya. *Agave* (*s.s.*) contains two well-defined subgenera (*Littea* and *Agave*), and glossophagine phyllostomid bats, especially species of *Leptonycteris*, are important pollinators of species in both subgenera (Rocha *et al.* 2006). Species of *Agave* (*s.s.*) are generally not as well-adapted to extreme aridity as cacti and tend to be distributed in moister upland sites in the Sonoran Desert. Nonetheless, about 40 of the 150 North American species occur in this region (Dimmitt 2000; Rocha *et al.* 2006). Good-Avila *et al.* (2006) and Rocha *et al.* (2006) suggest that the presence of large, arid zone bat-pollinated cacti set the stage for the evolution of tall *Agaves* (*s.l.*) that produce nectar-rich flowers attractive to bats. Production of a large, energetically expensive paniculate inflorescence in *Agave* (*s.s.*), in turn, selected for a monocarpic 'suicidal' life history, which is a derived condition in this family.

Members of the endemic American leaf-nosed bat family Phyllostomidae are pollinators of columnar cacti and paniculate agaves throughout the Neotropics. This family contains about 150 species and evolved about 36 mya; its crown groups arose in the late Oligocene, 26–28 mya (Jones *et al.* 2005; Teeling *et al.* 2005). Insectivory is the ancestral diet in the family, but its current dietary diversity is substantial and includes blood-feeding, vertebrate carnivory, nectarivory, and frugivory. The main clade of nectar-feeding phyllostomids (subfamily Glossophaginae *sensu lato*) evolved about 12 mya and contains about 38 species (Davalos 2004, Simmons 2005). Although several species of nectar- and fruit-eating phyllostomids visit and presumably pollinate flowers of columnar cacti, members of one glossophagine genus, *Leptonycteris*, which contains three species, are the primary pollinators of columnar cacti and agaves in Greater Mexico (*L. yerbabuenae* and *L. nivalis*) and northern South America (*L. curasoae*) (Fleming and Nassar 2002; Simmons and Wetterer 2002).

Leptonycteris yerbabuenae (formerly *L. curasoae*) is the main chiropteran cactus and agave pollinator in the Sonoran Desert. Its population biology is complex and includes migratory and resident populations and two reproductive schedules in Mexico (Fleming and Nassar 2002). Females living in the Pacific coastal region of south-central Mexico mate in November and December and migrate north to the Sonoran Desert to have their babies in mid-to-late May. Several substantial maternity roosts containing tens of thousands to over one hundred thousand adult females are known in the Sonoran region (Wilkinson and Fleming 1996, Fleming and Nassar 2002, Peñalba *et al.* 2006). These roosts disband in late summer with some females and young moving into the uplands of southern and southeastern Arizona to feed on the nectar and pollen of *Agave palmeri* (which includes *A. chrysantha)* while others begin to migrate toward southern Mexico. Populations of *L. curasoae* living in Baja California appear to be year-round residents there, and several maternity roosts are known on the Baja mainland and surrounding islands (Wilkinson and Fleming 1996, W. Frick, pers. comm.). Spring births also occur in these populations. In contrast, populations living in southern Mexico mate in the summer and give birth in December and January when bat-pollinated tropical trees are in peak bloom.

3. POLLINATION BIOLOGY OF SONORAN DESERT COLUMNAR CACTI

Flowering is a spring and early summer event in the four main columnar cacti that we treat in this chapter. Peak flowering in cardon and saguaro usually occurs in late April through mid-May whereas peak flowering in organ pipe occurs in June. Flowering in senita occurs in several pulses between April and July. Fruit set in cardon (females only in this trioecious species; see below) and organ pipe is pollen-limited but is resource-limited in saguaro, senita, and hermaphrodites of cardon (Fleming *et al.* 1996, 2001).

Although saguaro, cardon, and organ pipe produce classic bat flowers (*i.e.*, they are large and white in color with nocturnal anthesis and copious amounts of nectar and pollen), pollinator exclusion experiments indicate that bats are relatively minor pollinators of saguaro (about 45% of fruit set) and organ pipe (about 30% of fruit set) but account for about 90% of fruit set in cardon (Fleming *et al.* 2001). Diurnal pollinators such as birds and bees account for more fruit set than bats in the former two species. White-winged doves are especially important pollinators of saguaro flowers whereas hummingbirds are important pollinators of organ pipe flowers. As a result, these Sonoran Desert columnar cacti have more generalized pollination systems involving both nocturnal and diurnal vertebrates and insects than their relatives farther south in Mexico and Venezuela, many of which rely exclusively on bats for pollination (Fleming 2002).

Our research has revealed two novel aspects about the pollination biology of these columnar cacti. First, cardon does not have a hermaphroditic breeding system as found in most Cactaceae (*e.g.*, saguaros, organ pipes, etchos [*Pachycereus pecten-aboriginum*], and senita). Instead, it has a *trioecious* breeding system in which hermaphroditic (bisexual) individuals co-occur with male and female (unisexual) individuals in some populations. This complex breeding system varies geographically with male plants being absent from the southern portion of cardon's range in coastal Sonora and in the northern portion of its range in Baja California (Fleming *et al.* 1998). Populations that lack males but which contain hermaphrodites and females are called *gynodioecious*. Initially, it was thought that this geographic variation reflected, and was caused by, geographic variation in the abundance of cardon's main pollinator, the bat *L. yerbabuenae*, but recent research has refuted this hypothesis (Fleming *et al.* 1998, Molina-Freaner *et al.* 2003).

Although we currently do not know what factor(s) is/are responsible for geographic variation in the form of cardon's breeding system, we do know why cardon has an odd (and extremely uncommon) breeding system. Unlike other members of *Pachycereus* (and most other cacti) that are diploid (*i.e.*, all chromosomes occur as pairs in individuals), *P. pringlei* is tetraploid (*i.e.*, all chromosomes occur in sets of four), a condition that often results in the loss of self-incompatibility barriers in flowering plants (Levin 1983). Most diploid columnar cacti in the Sonoran Desert (and elsewhere) are self-incompatible and must receive pollen from another individual for successful fertilization and seed production. In contrast, hermaphrodites of cardon are self-compatible, and individuals can fertilize their own ovules. Self-fertilization in many plants leads to the production of inferior offspring that suffer from inbreeding depression (the loss of fitness through the deleterious effects of recessive mutations). Self-compatibility and inbreeding depression, in turn, can select for mechanisms that promote out-crossing (genetic exchange between different individuals), and one of these mechanisms is the production of unisexual individuals (*i.e.*, separate males and females) through the occurrence of genetic mutations causing male or female sterility. Male sterile individuals are females that transmit their genes from one generation to the next only via seeds whereas female sterile individuals are males that transmit their genes only via pollen. Hermaphrodites, in contrast, possess both male and female sex functions and can transmit their genes via both pollen and seeds.

Knowing that hermaphrodites have a two-fold advantage in reproduction over unisexual individuals, we can ask, how do males and females persist in populations with hermaphrodites? One way they could do this is if the cost of inbreeding in hermaphrodites was very high, so that their inbred offspring were much less competitive than the outcrossed offspring of females. But through a series of observations and experiments, we know that this is not likely to be true: inbred seedlings of hermaphrodites survive and grow just as well as those of females both in the field and in the lab, at least during their first two years of life (Sosa and Fleming 1999). Another way by which females and males can successfully compete with hermaphrodites is by outproducing them in terms of seed and pollen production. Intuitively, we might expect females to produce twice as many seeds and males to produce twice as much pollen per season as hermaphrodites if they are to remain in the evolutionary game. Data on seed and pollen production in several cardon populations in Sonora over several years indicate that females and males indeed outproduce hermaphrodites in both seed and pollen production by factors of 1.6–9.3 (Fleming *et al.* 1994, Molina-Freaner *et al.* 2003), which helps to explain why they are able to coexist with bisexual individuals, even in the face of apparently low levels of inbreeding depression in seedlings of hermaphrodites.

The second novel aspect of the pollination systems of Sonoran Desert columnar cacti occurs in organ pipe, *S. thurberi*. As indicated above, peak flowering in this cactus occurs in June, after the flowering peaks of cardon and saguaro, but observations of marked plants indicate that some individuals (about 25% at Bahía de Kino, Sonora) routinely begin flowering in early April, well before the bulk of the population. Early-flowering organ pipes are faced with strong competition for bats and other pollinators from cardon and saguaro and are highly likely to receive heterospecific, rather than conspecific, pollen from bat visits. In most plants, receipt of heterospecific pollen causes flowers to abort, but this does not happen in organ pipe. Carefully controlled hand pollination experiments indicate that when cardon pollen is placed on organ pipe stigmas, fruit set is nearly as high (74%) as when conspecific pollen is placed on their stigmas (84%); cardon flowers abort when they receive organ pipe pollen (Fleming 2006). Compared with fruit from flowers receiving conspecific pollen, heterospecific fruit develop more slowly, are smaller at maturity, and contain fewer and smaller seeds. Most importantly, seeds in heterospecific fruits lack embryos and hence are sterile. Comparison of the growth rates of open-pollinated fruits with those of conspecific or heterospecific fruits indicate that between early April and mid-May, most fruits are derived from heterospecific pollination.

These observations and experiments indicate that, unlike cardon and saguaro, organ pipe can use heterospecific pollen to produce fruits that mature but contain sterile seeds. This fruit retention is odd and raises the question, why hasn't selection eliminated early flowering in this species? One explanation for the existence of early flowering in coastal Sonora is that it has positive selective value at sites that lack cardons (*i.e.*, in much of *S. thurberi's* range in Sonora; see Figure 1) because it enables individuals to attract migrating populations of nectar-feeding bats and hummingbirds (Fleming 2006). Levels of between-population gene flow, mediated by strong-flying *Leptonycteris* bats, are known to be high in organ pipe (as well as in cardon and saguaro; Hamrick *et al.* 2002) which might make it difficult for selection to remove early flowering genes from coastal populations.

In Sonora, *S. thurberi* apparently has a geographic 'refuge' from a strong competitor, *P. pringlei*, but what about in Baja California, where the ranges of organ pipe and cardon overlap completely (see Figure 1)? Based on the results from Bahía de Kino, we might expect early flowering in organ pipe to be much less common in Baja than in Sonora, but this apparently is not the case. In the area around Loreto, Baja California Sur, between 18–22 April 2009, the frequency of early flowering in

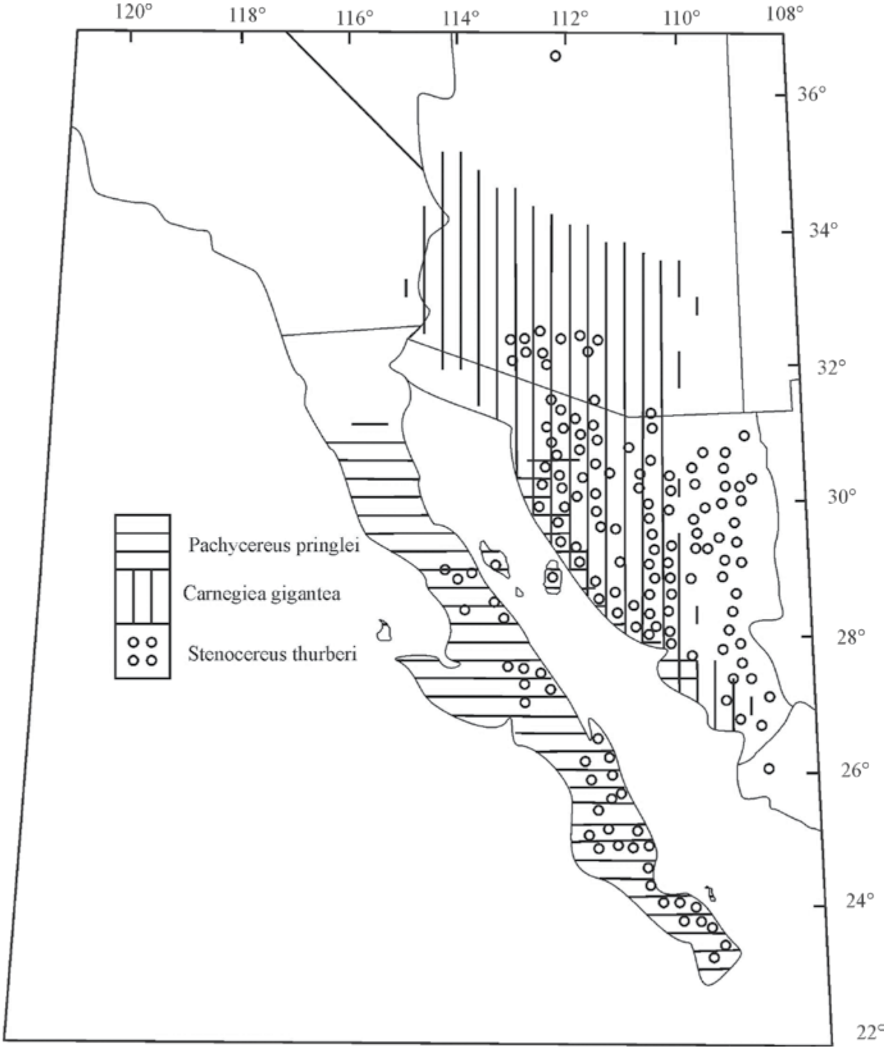

FIGURE 1. Map of the distribution of three species of Sonoran Desert columnar cacti: cardon (*Pachycereus pringlei*), organ pipe (*Stenocereus thurberi*), and saguaro (*Carnegiea gigantea*).

two populations of organ pipe was 14% (n = 56 plants) and 38% (n = 37), values that are similar to those reported for Sonora at a similar time of the year (Fleming 2006, unpubl. data). Early flowering is thus not uncommon in southern Baja. What was different about flowers of Loreto organ pipes compared with those is Sonora is that they were open by mid-afternoon rather than opening after sunset, and their tepals were erect rather than reflexed, making their corollas more tubular in shape. The Loreto flowers were being visited by two species of hummingbirds in the afternoon as well as by *Leptonycteris* bats at night; they closed early the next morning as they do in Sonora (T. Fleming, pers. obs.). Although a detailed study of the pollination biology of *S. thurberi* in Baja California needs to be done, these preliminary observations suggest that this species has shifted from a strongly nocturnal/weakly diurnal flowering pattern as occurs in Sonora to a more balanced diurnal/nocturnal flowering pattern with a greater emphasis on hummingbird pollination in Baja. Timing of anthesis, pattern of nectar production, and flower form all seem to differ in Baja compared with Sonora. The net result of these differences is potentially lower competition for pollinators between organ pipe and cardon and reduced loss of fitness as a result of heterospecific pollination in Baja.

A similar shift away from nocturnal pollination toward diurnal pollination has also occurred in saguaro, the columnar cactus with the most northern distribution in North America (see Figure 1). Compared with cardon and organ pipe, flowers of saguaro open later at night and close much later the next afternoon (Fleming *et al.* 1996). Whereas rate of nectar production has a single peak before midnight in cardon and organ pipe, nectar production in saguaro has two peaks, one at about 0200 and another at 0800. Saguaro has clearly moved from the strongly nocturnal/weakly diurnal flowering pattern seen in most bat-pollinated columnar cacti to a weakly nocturnal/strongly diurnal pattern, probably because of the low density or absence of *Leptonycteris* bats in much of the northern part of its geographic range (Fleming *et al.* 2001, Fleming 2002).

The fourth species of Sonoran Desert columnar cactus studied by Fleming, Holland, and their associates is senita, *Pachycereus schottii*. Producing relatively small white or pink actinomorphic (radially symmetrical) flowers that open just after sunset and offer little or no nectar reward, this cactus clearly is insect-pollinated. Rather than being pollinated by hawkmoths, which occasionally visit bat-pollinated cacti, however, the pollinator of senita is a small pyralid moth, *Upiga virescens* (the senita moth), whose entire life cycle is physically associated with this cactus (Fleming and Holland 1998, Holland and Fleming 1999a). During the day, adults of this species rest in the long, bristle-like spines located at the tops of branches. As soon as flowers open at night, they are visited by female senita moths which rub their abdomens over the anthers, collecting pollen on elongated abdomenal setae and scales. Females then fly off to find another individual of this self-incompatible species to pollinate. When they arrive at another plant, females climb onto the stigma of a flower and rub pollen on it in an act of *active pollination* (cf. passive pollination as practiced by bats, birds, and bees as they seek a tongueful of nectar). Active pollination is very uncommon in plant-pollinator interactions and is best documented in the yucca/yucca moth and fig/fig wasp pollination mutualisms. In these well-studied interactions, females oviposit one or more eggs in a flower's ovary before or after pollination, and their larvae eat and destroy seeds. A similar situation obtains in the senita/senita moth interaction because after pollinating a flower, females lay a single egg on the tips of flower petals or among anthers in the corolla. After the eggs hatch, larvae chew into the ovary and eat developing seeds. They then chew out of the fruit, causing it to abort, and pupate in the stem beneath the areole supporting that fruit. Not all larvae survive long enough to destroy seeds and fruit, and pollination by female moths produces about four to five times more mature fruit than are destroyed by their larvae (Holland and Fleming 1999b). Thus, like the yucca/yucca moth and fig/fig wasp interactions, the senita/senita moth interaction has a net positive effect on plant reproductive success and should be considered mutualistic rather than parasitic. Finally, on warm nights, senita flowers close before sunrise, making *U. virescens* their sole pollinator. On cold nights, flowers remain open for a short time after sunrise and are visited by halictid bees, which are legitimate pollinators (Holland and Fleming 2002). The vast majority of senita fruits, however, result from pollination by female senita moths, and this pollination interaction is thus much more specialized than the pollination systems of saguaro, cardon, and organ pipe.

In addition to *S. thurberi*, the pollination biology and population structure of two other species of *Stenocereus* that occur in Baja California have been studied in detail (Clark-Tapia and Molina-Freaner 2003, 2004, Molina-Freaner and Clark-Tapia 2005). These two closely related species include *S. gummosus*, which can be considered to be a small columnar cactus reaching only a couple of meters in height, and *S. eruca*, which is a prostrate cactus called the 'creeping devil' (Yetman 2007). Both species flower in the summer and fall, and both are self-incompatible hermaphrodites (Clark-Tapia and Molina-Freaner 2004). Although flowers of both species are mostly nocturnal and are pollinated by sphingid moths and native bees, the relative importance of sexual vs. asexual reproduction differs strongly between them. Flowers of *S. gummosus* are reliably visited by moths, and fruit set is similar (40–60%) to that of other Sonoran Desert columnar cacti in most years. In contrast, pollinator visitation in *S. eruca* is highly erratic, and fruit set is very low (3–15%) in good years and 0% in bad years. As a result, clonal propagation is much more important for regeneration in *S. eruca* than in *S. gummosus*. Not surprisingly, populations of *S. eruca* contain less genetic variation and are much more structured genetically (*i.e.*, genotypes are strongly clumped) than those of *S. gummosus* (Molina-Freaner and

Clark-Tapia 2005). Pollinator unreliability has likely favored an emphasis on clonal rather than sexual reproduction in *S. eruca*.

Pollinator unreliability resulting from (1) outright absence of ancestral pollinators (as in *C. gigantea*), (2) strong year-to-year variation in the abundance of sedentary insect pollinators (as in *S. eruca*) or migratory vertebrate pollinators (as in *C. gigantea*, *P. pringlei*, and *S. thurberi*), or (3) strong competition for pollinators from other cacti (as in *S. thurberi*) has had a strong effect on the pollination and reproductive biology of Sonoran Desert columnar cacti. Of the species that we have studied, only senita (*P. schottii*) has evolved a highly specialized relationship with a single species of pollinator, the senita moth. The other species rely on a variety of species, including both nocturnal and diurnal vertebrates and insects in the case of the large columnars, for pollination. In this respect, these plants are no different from flowering plants in many other habitats and regions. Generalization, rather than narrow specialization, characterizes the relationships between many plants and their pollinators, particularly in extra-tropical regions (Waser *et al.* 1996). Do we see a similar emphasis on pollinator generalization in Sonoran Desert agaves, whose reproduction relies on the same suite of potential pollinators?

4. POLLINATION BIOLOGY OF SONORAN DESERT AGAVACEAE

As indicated above, relatively few species of *Agave* inhabit lowland portions of the Sonoran Desert, and the pollination biology of only two species has been studied in detail. These species include *A. subsimplex*, which occurs in a few small colonies in coastal Sonora, and *A. angustifolia*, which is widely distributed in the coastal lowlands to mid-elevations of Mexico and Central America (Gentry 1982). Both species are self-incompatible hermaphrodites that flower in late winter and spring in central Sonora (Molina-Freaner and Eguiarte 2003). Observations of pollinator visitations indicate that bats, birds (hummingbirds, orioles, and woodpeckers), and insects (moths and introduced and native bees) visit flowers of both species, but pollinator exclusion experiments indicate that the bat *L. yerbabuenae* is the only effective pollinator of *A. angustifolia* whereas both nocturnal and diurnal pollinators are effective in *A. subsimplex*. Molina-Freaner and Eguiarte (2003) concluded that *A. angustifolia* resembles tropical Mexican agaves in its strong dependence on bats for pollination and that *A. subsimplex* resembles extra-tropical *Agave*s (*e.g.*, *A. palmeri/chrysantha* in southeastern Arizona; Slauson 2000) by having a more generalized pollination system. These results are similar to the situation in Mexican columnar cacti in which extra-tropical species have more generalized pollination systems than bat-pollinated tropical species (Fleming *et al.* 2001, Fleming 2002).

5. SYNTHESIS AND CONCLUSIONS

Available data on the pollination biology of Sonoran Desert columnar cacti and paniculate agaves indicate that these systems fall along a continuum between strong specialization and total generalization (*fide* Waser *et al.* 1996) with pollinator reliability being a strong determinate of where particular species fall on this continuum. The senita/senita moth interaction is clearly the most specialized of these pollination systems. Indeed, because of active pollination, it is one of the most specialized pollination systems in the world. While we generally expect to find most highly specialized mutualistic interactions to occur in the tropics because of its perceived climatic stability and year-round growing season, it is interesting to note that two of the world's most specialized and coevolved pollination systems —the yucca/yucca moth and senita/senita moth systems— occur in extra-tropical and often strongly arid, climatically variable habitats. We conclude from this that climatic stability is not a *sine qua non* for the evolution of highly specialized pollination systems. In the case of the yucca and senita systems, it has been postulated that nocturnal anthesis, self-incompatibility, and resource-limited fruit set, rather than climatic stability or pollen-limited fruit set, have been particularly important factors in the evolution of these systems (Pellmyr *et al.* 1996, Fleming and Holland 1998).

The next most specialized pollination systems include *Stenocereus gummosus* and *S. eruca*, which are pollinated by sphingid moths, and *Pachycereus pringlei* and *Agave angustifolia*, which are pollinated by *Leptonycteris* bats. Although these plants rely heavily on particular nocturnal animals for pollination, their pollinators are not nearly as restricted and visit a variety of different flowers for nectar and pollen. As a result, these systems represent asymmetrical mutualisms in which the plants are more dependent on particular kinds of pollinators than their pollinators are on particular kinds of plants. Over an entire annual cycle, for example, *L. yerbabuenae* is known to feed on the flowers of many species of columnar cacti as well as spicate and paniculate agaves and a variety of tropical trees and shrubs (Fleming and Nassar 2002, Rocha *et al.* 2006). Similarly, the hawkmoth *Hyles lineata*, which pollinates *S. gummosus* and visits many other cactus and non-cactus flowers, has a broad diet (Alarcón *et al.* 2008). Finally, the most generalized pollination systems include those of *Carnegiea gigantea* and *Stenocereus thurberi* and *Agave subsimplex.* Both diurnal and nocturnal vertebrates as well as diurnal insects are known to effectively pollinate these plants. It is tempting to postulate that generalized pollination systems have evolved in these species because of a combination of (1) their geographic distributions (*C. gigantea*, *A. subsimplex*) and/or (2) their reduced attractiveness to nectar-feeding bats when they co-occur with a superior competitor (*C. gigantea*, *S. thurberi*).

A northern distribution or restricted distribution reduces the exposure of *C. gigantea* and *A. subsimplex* to chiropteran pollinators, respectively. Because of its high density and greater number of open flowers per night, *P. pringlei* likely is a superior competitor for bat visits, to judge from its higher flower visitation rates, than *C. gigantea* and *S. thurberi* when all three species co-occur at the same site (Fleming *et al.* 1996). Again, as we discussed above, reliability of particular kinds of pollinators, especially *Leptonycteris* bats, has played an important role in the evolution of the pollination systems of several species of Sonoran Desert succulents.

In addition to detailed studies of the pollination systems of Sonoran Desert columnar cacti and agaves, our research has revealed new complexities in the reproductive biology of some of these plants. Totally unexpected was the trioecious breeding system of cardon, which is one of the world's largest cacti. Such a complex breeding system in a long-lived plant is unexpected. Other plants with trioecious breeding systems (*e.g.*, wild thyme, *Thymelea hirsuta*) are small, relatively short-lived species. As discussed by Murawski *et al.* (1994) and Fleming *et al.* (1994), a ploidy event in which *P. pringlei* doubled its chromosome number autonomously from a haploid number of 11 that occurs in most cacti to 22 set the stage for the successful invasion of unisexual individuals into populations of hermaphrodites. According to Levin (1983), such ploidy events are not unusual in plants living in extreme environments.

Also unexpected was organ pipe's ability to set seed with heterospecific pollen. Neither cardon nor saguaro has the ability to do this (Alcorn *et al.* 1962, Fleming 2006). Whether other species of *Stenocereus* can do this is presently unknown. This ability likely has negative fitness consequences for *S. thurberi* because it wastes resources through the production of sterile fruits weighing ≥ 50 g. We cannot think of a reason why this ability might have positive selective value in a desert setting.

In conclusion, Sonoran Desert columnar cacti and paniculate agaves living at the northern limits of their clades' geographic distributions have had to adapt to physiologically and biologically challenging environments. In terms of their pollination biology, their biggest challenge has been to adapt to significant spatial and temporal variation in the abundance of their pollinators. Virtually all vertebrate pollinators in this region are migratory, and their numbers at particular sites vary substantially from year to year (Fleming *et al.* 2001). Less is known about year-year fluctuations in the abundance of moth and bee populations in this desert, but to judge from the high annual variation in fruit set in *Stenocereus eruca* in Baja California, some insect populations are also likely to be highly variable in size. Bat pollination is likely to be ancestral in the Pachycereeae, but because *Leptonycteris* bats are migratory in the Sonoran Desert, two of three ostensibly bat-pollinated columnar cacti and one of two paniculate agaves there rely less on them for pollination than their southern relatives. An extreme response to pollinator unreliability —giving up sexual reproduction altogether— occurs in the prostrate cactus *S. eruca*, which evolved from *S. gummosus* in the dunes of west-central Baja California (Molina-Freaner and Clark-Tapia 2005). Vegetative, rather than sexual, reproduction is much more important in *eruca* than in *gummosus*.

Our final conclusion deals with the conservation implications of the pollination biology of Sonoran Desert columnar cacti and agaves. Sexual reproduction is important, at least at times, in the lives of virtually all of the large northern cacti and agaves, and vertebrate and insect pollinators are intimately involved in this process. Anything that has a negative effect on populations of these pollinators will also have a negative effect on the reproductive success and demography of their food plants. Many of the most important Sonoran Desert vertebrate pollinators, including *Leptonycteris* bats, certain hummingbirds, and white-winged doves, are only seasonal residents in this region (see chapters in Nabhan 2004), and their lives are particularly vulnerable to disruption in a number of different ways. Loss of habitat containing food resources and safe nesting and roosting sites is probably the greatest threat to most migratory animals (Fleming and Eby 2003, Fleming 2004). Mesquite bosques, for example, are an important nesting habitat for white-winged doves, and loss of this habitat has had a profound effect on certain populations of this dove (Martinez de Rio *et al.* 2004). Similarly, *Leptonycteris* bats use a limited number of caves as traditional mating and maternity roosts in Mexico and southern Arizona. When Colossal Cave east of Tucson was commercialized in the 1960s, *L. yerbabuenae* lost one of only four known maternity roosts in Arizona (Cockrum and Petryszyn 1991). Further loss of such roosts would have a devastating effect on this species at the northern limits of its geographic range. Likewise, Fleming (2004) estimated that females of *L. yerbabuenae* need to make at least two stopovers for replenishing their fat reserves when migrating from mating roosts in Jalisco to maternity roosts in the Sonoran Desert. Flowers of columnar cacti (*e.g.*, *Pachycereus pecten-arboriginum*) are an important food (fuel) source during this migration. Anything that disturbs their stopover roosts or food supplies in tropical dry forest and thornscrub along Mexico's Pacific coast will endanger this migration and, ultimately, the reproductive success of Sonoran Desert plants that depend on these bats for pollination. Similar concerns hold for *Leptonycteris* bats and their food plants in Baja California and for habitats, roosts, and food plants used by these bats during their southward fall migration in mainland Mexico. The bottom line is this: the reproductive success and persistence of many charismatic Sonoran Desert plants are now being threatened by factors both within and outside of this region. Within this region habitat conversion and bufflegrass (*Pennisetum ciliare*) invasion threaten or destroy populations of columnar cacti and agaves (Morales-Romero and Molina-Freaner 2008). Similar forces in western Mexico as far south as Jalisco pose a similar threat. Habitat conservation throughout the Pacific coast of Mexico is critical for the health of populations of charismatic Sonoran Desert plants and their animal pollinators.

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DIAGNOSIS OF DEGRADED AREAS AND PROPOSALS FOR ECOLOGICAL RESTORATION IN BAJA CALIFORNIA SUR

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Areas that show ecological degradation processes in Baja California Sur, Mexico, were identified by means of land-cover analysis through spatial analysis of information in a geographical information system (GIS) and the application of a vegetation index (VI). Seven areas are recognized as critical in the north, central and south portions of the state. All seven present soil degradation to some extent from 1990 to 2000. Corrective measures are recommended in order to revert or minimize this process.

1. INTRODUCTION

The studies of land-cover and land-use change are at present at the center of attention of environmental research. The importance of knowing the state of the environment resides in the need to have real and quantifiable elements to be used in the decision making processes regarding the use and management of natural resources. In Mexico, the study of the magnitude, dynamics and causality of land-cover and land-use change is a priority. Data obtained by Masera *et al.* (1997) indicate that Mexico ranks among the nations with higher deforestation rate in the world.

The state of Baja California Sur, in the extreme north-west of Mexico, is no exception. The great biological richness of its arid zones is each year seriously affected by land-use changes. These changes impact the physical and biological environment, eroding the soil and modifying the habitat, the biological interactions of their wild populations, the animal behavior, and the ecosystem processes. Additionally, they accelerate the introduction of invasive species and increase the fragmentation of wild areas near roads and rural and urban developments (Trombulak and Frissell 2000, Nellemann 2001, Arriaga *et al.* 2004, Arriaga 2009).

Understanding the impact of land-use and land-cover changes implies the study of coupled environmental and socio-economic factors (Bocco *et al.* 2001). Current land-use has important implications in the future climate of the earth and consequently great feed-back implications for future land-use (Agarwal *et al.* 2002), a powerful reason to understand the interactions between human activities and natural resources. Land-use change is an extensive, accelerated, and momentous process caused by human action and changing the face of the earth, and in many cases it also causes changes that negatively impact human populations and their ability to derive sustenance from their environment (Rosete-Vergés *et al.* 2008).

Most changes in terrestrial ecosystems are due to one or more of these factors: (a) land-cover conversion, (b) land degradation, and (c) land-use intensification. These processes, usually grouped in what is known as *deforestation* or *forest degradation*, are associated with important ecological impacts at virtually all scales: locally they induce the loss and degradation of soil, cause changes in the microclimate and promote the loss of species diversity; regionally they affect the dynamics of entire basins, ecosystems and human settlements; and at a global level they contribute to greenhouse-gas emissions which drive global climate change (Bocco *et al.* 2001).

Land-use changes are commonly separated from land-cover changes despite the similarities in methods and approaches (Weng 2002). According to Brown *et al.* (2000) in border regions with economies based mainly in extractive economies (*i.e.*, mostly in developing countries), land-use and land-cover are almost always semantically equivalent. For example, the activity of land-use associated to logging leads to a land-cover with reduced tree cover or no trees (Lambin 1997). However, in a post-modern economy that is led by information and information access, as most of modern Europe and the United States, land-use and land-cover seem to be less equivalent (Brown *et al.* 2000).

A form of assessing the dynamics of land-use change is by measuring changes in vegetation cover and non-vegetated land uses. Traditionally the measurement of land-cover and land-use change is done through remote sensing (usually aerial photographs and satellite imagery) or thematic mapping. Pragmatically, the concept of the term "land-cover" describes the objects distributed over a specific territory, while "land-use" refers to the result of the socio-economic activities that are (or were) taking place in a particular land-cover type. These activities are related to the appropriation of natural resources used to generate goods or services (Bocco *et al.* 2001).

The investigation presented in this chapter was carried out in order to determine which ecologically degraded zones in the state of Baja California Sur, Mexico require urgent attention. In this context, our results establish seven critical zones, determine the extension of their degradation, the basins to which they belong, the types of vegetation affected and the recommended corrective measures to stop this accelerated process.

2. METHODS

Our approach was based on the analysis of changes of vegetation cover from satellite imagery, using NOAA-AVHRR[1], LANDSAT TM[2], and LANDSAT ETM[3] images. A vegetation index (VI) was applied to quantify the changes in vegetation cover and locate the areas with most degradation or susceptibility to it. Results were tested against independent information on land-use and vegetation for the state of Baja California Sur (B.C.S.) obtained from CONABIO (1998).

The vegetation indices commonly used to understand the characteristics and dynamics of natural and induced vegetation are the product of algorithms applied to low-cost sensors such as NOAA-AVHRR (Rouse 1974, Holben 1986, Santiago León 2003) and medium-cost such as the Landsat series (Santiago León 2003).

The information provided by satellite imagery provides many elements that are potentially apt to be applied in the evaluation of natural resources in time series. As a result of this work a database with information of the degraded areas or areas in process of environmental degradation in B.C.S. was generated, and preliminary recommendations were proposed for the ecological restoration of the critical areas.

2.1. Procedure 1: analysis of NOAA-AVHRR images

The AVHRR system was conceived as a scanning radiometer for meteorological purposes and was first launched on a polar-orbiting satellite in 1978. But the data it provides have allowed to develop applications in the field of Earth observation, and since then it has come to be one of the most valuable sources of data for non-meteorological purposes in a whole variety of environmental, scientific, and management contexts (Goodrum 1999, Cracknell 2001, Suárez-Seoane 2005).

From the total bands of the NOAA-AVHRR satellite, two provide relevant information to calculate the VI, considering the response of the vegetation to the red and near-infrared spectral ranges:

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[1] NOAA–AVHRR: National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer.

[2] TM: Thematic Mapper from NASA Landsat Program.

[3] ETM: Enhanced Thematic Mapper from NASA Landsat Program.

- Band 1 (0.580-0.680 μm): chlorophyll absorption range
- Band 2 (0.725-1.100 μm): vegetation reflectance

The Normalized Difference Vegetation Index, or NDVI, is then calculated applying the following formula:

$$\mathrm{NDVI} = \frac{\mathrm{NIR\text{-}RED}}{\mathrm{NIR{+}RED}} = \frac{\mathrm{band2\text{-}band1}}{\mathrm{band2{+}band1}}$$

Ten NOAA-AVHRR GAC[4] hemispheric images of 8 km pixel size were used (Maselli *et al.* 2002). Their analysis provided a panoramic view of the vegetation index (VI) ranges in the zone of study and a preliminary reference to delimitate the analysis to the period from August to October, the rainy season when the vegetation index for this normally arid region shows larger contrasts and is more stable. The general areas that present notorious changes in their VI were identified with this procedure and a more detailed analysis was centered on these areas.

The VI change analysis was made in a ten-year time series from 1990 to 2000, using 20 and 15 NOAA-AVHRR LAC[5] images respectively. Each of these 35 satellite images has a spatial resolution of 1 km. The totality of the state of Baja California Sur was included in this coverage. Areas that present a significant VI change were delimited from this analysis.

Before any analysis is conducted all satellite images must be geometrically and radiometrically corrected. To ensure the quality of the results adjustments were made on: (1) signal degradation, (2) cloudiness, (3) atmospheric conditions (aerosols, water vapor, etc.), (4) observation point, and (5) ground effects (geology).

For the representation of the vegetation index a color palette (false color) was applied on the images. Additionally, compounds of images of daily indices were used, from which the Maximum Value Composite (MVC) was obtained (Holben 1986). This allowed us to minimize the problems caused by the atmospheric effects and observation angles, which often complicate the use and interpretation of images (Cocero *et al.* 2000).

2.2. Procedure 2: analysis of LANDSAT TM and ETM images

Once the pre-selection of the sites was concluded, we proceeded to derive the VI with more detail from the 30 m resolution images of Landsat TM and ETM

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[4] GAC, Global Area Coverage denominated for global or hemispheric coverages obtained from NOAA-AVHRR with resolution of 8 and 16 km.

[5] LAC, Local Area Coverage denominated for the type of image obtained from the NOAA-AVHRR satellite series with 1 and 4 km resolution options.

TABLE 1. Characteristics of the Landsat TM and ETM images. Bands 3 and 4 are used to derive the vegetation indices (http://landsat7.usgs.gov/project_facts/history/)

Band	Spectral range	Resolution in meters	Satellite
1	Visible (0.45 – 0.52µm)	30	TM, ETM
2	Visible (0.52 – 0.60µm)	30	TM, ETM
3	**Visible (0.63 – 0.69µm)**	**30**	**TM, ETM**
4	**NIR[i] (0.76 – 0.90µm)**	**30**	**TM, ETM**
5	NIR (1.55 – 1.75µm)	30	TM, ETM
6	Thermal (10.40 – 12.50µm)	120	TM
6*	Thermal (10.40 – 12.50µm)	60	ETM
	Low Gain / High Gain		
7	Mid IR (2.08 – 2.35µm)	30	TM, ETM
8	Panchromatic (PAN) (0.52 – 0.90µm)	15	ETM

satellites. As in the previous procedure, VI change analysis was calculated on a time series from 1990 to 2000. To have a full coverage of the state we used a total of 16 images, 8 for each year (information was obtained from the server at the University of Maryland).

The analysis of Landsat TM and ETM images to calculate the VI was also based on the principles of vegetation response to the spectral ranges of red and near-infrared. Like in the previous procedure the NDVI was applied, substituting the corresponding band for these satellites as shown in Table 1.

$$\mathrm{NDVI} = \frac{\mathrm{NIR\text{-}RED}}{\mathrm{NIR+RED}} = \frac{\mathrm{band4\text{-}band3}}{\mathrm{band4+band3}}$$

As before, each image was geometrically and radiometrically corrected prior to their analysis. It is important to mention that the analysis performed was affected by the characteristics of vegetation and geology of Baja California Sur, due to high reflectance of the study area, resulting in the loss of high quality signal from vegetation indices; however, the above methodology seeks to minimize these problems.

The range of values obtained using the NDVI goes from -1 to +1. Only positive values correspond to areas with vegetation, negatives indicate bare soil (Suárez-Seoane 2005). For purposes of the analysis only positive values (greater than zero) were used in order to simplify the processes and to focus the analysis.

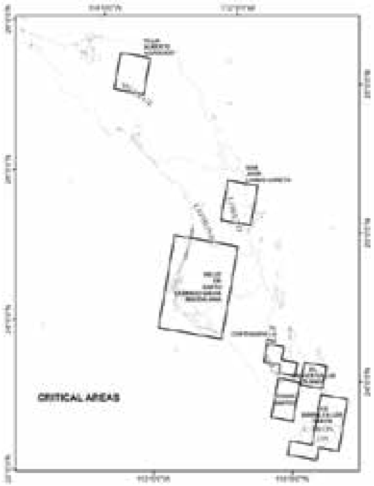

FIGURE 1. Location of areas with important changes in VI from 1990 to 2000 in the state of Baja California Sur, México. Results derived from NOAA-AVHRR 8km and 1km the image analysis. Ortega Rubio and Santiago Leon 2005.

2.3. Procedure 3: Contrasting results with existing information

In order to refer the results to known geographic elements in the study area, we used a series of regional thematic maps, including (a) Surface Hydrology and Basins (CONABIO 1998), (b) Land-Use and Vegetation (Inventario Forestal 2000), (c) Roads and Towns, and (d) municipal and state boundaries (obtained from INEGI). Layering of maps was performed using a Geographic Information ArcGIS. Finally, after contrasting the VI obtained and contrasting its consistency against other thematic maps, we proceeded to select priority sites. For practical purposes, each site was assigned the name of the main locality within it.

3. RESULTS

Comparing the vegetation indices (VI) derived from the NOAA-AVHRR images at 8 km resolution from the years 1990 and 2000; significant changes were observed in the northern, central and southern parts of the State of Baja California Sur. Subsequently, and as a result of the analysis of NOAA-AVHRR 1 km images, seven areas were identified in which a significant change in VI was detected and thus important changes in land-use were inferred to have taken place. When referencing our results with the existing information it was found that the critical areas correspond to urban centers, agriculture areas, and extensive ranching sites (see Figure 1).

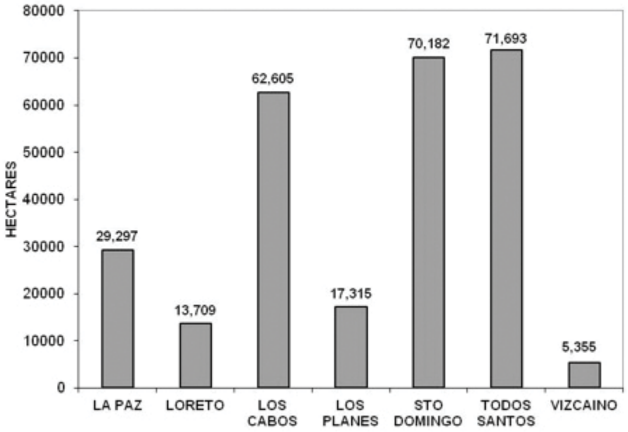

FIGURE 2. Degraded area for each critical site, measured in hectares.

The value of VI is proportional to amount of natural cover and is an indicator of vulnerability to soil degradation. A low VI corresponds to deforested areas that are more susceptible to soil degradation. In agreement to this criterion the areas selected from NOAA-AVHRR image analysis are listed below; listed on a top-down VI hierarchy:

- Los Cabos (Los Barriles-Cabo San Lucas)
- Santo Domingo (Santo Domingo–Bahía Magdalena)
- La Paz (El Centenario–La Paz)
- Todos Santos
- Los Planes (El Sargento–Los Planes)
- Loreto (San Juan Londó–Loreto)
- Vizcaíno (Villa Alvarado)

3.1. Synthesis of results: Areas under some type of soil degradation stress

Within each critical area, the total degraded area was estimated in hectares and the vegetation type most affected by land-use change was identified. A synthesis of these results is presented below. Purple markings on the image represent sites with high VI change between 1990 and 2000.

The sites with greater affected area were Todos Santos and Santo Domingo, both with over 70,000 ha showing signs of degradation through land-use change (see Figure 2). Los Cabos ranked slightly below this figure, with some 62,000 hectares

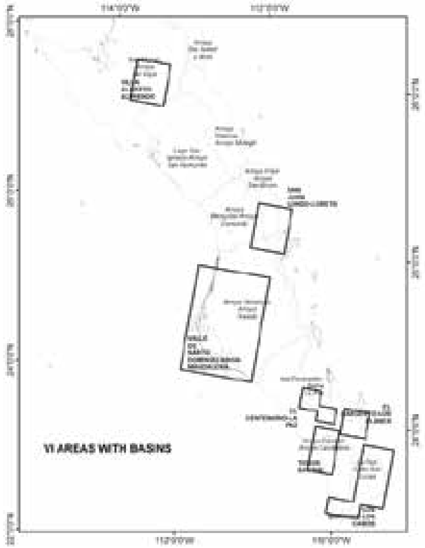

FIGURE 3. Overlapping of high VI change areas with basins of the B.C.S. state.

affected by land-use change, but showed a rate of decline in the overall VI values much higher than that of any of the other sites. The total area showing significant loss or degradation of native vegetation cover between 1990 and 2000 is 270,157 hectares, corresponding to 4% of the land surface of the State of Baja California Sur[6].

There is a spatial association between our critical areas, as defined by rapidly declining VI values, and the main water basins in the State (see Figure 3). The overlap between the areas of rapid land-use change and their sustaining basins provides an important element to analyze the potential impact of vegetation loss and soil degradation on water supply and aquifer recharge. Eight of the ten main basins of the state are to some extent contained within the polygons of our selected critical sites (see Table 2).

4. DISCUSSION AND CONCLUSIONS

The use of 8 km pixel size images from NOAA-AVHRR provided an overview of the range of vegetation indices (VI) in the State. The preliminary analysis provided

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[6] The percentage corresponds to area of study. The total area of Baja California Sur state calculated by GIS according to INEGI data is 7,060,736 ha; this number does not include islands.

TABLE 2. Critical selected sites, basins to which they belong and main land-use activities realized in each site.

Critical site	Basins	Degraded surface (ha)	Main land-use activities
La Paz	Arroyo Caracol-Arroyo Candelaria Isla Coronados-Bahía La Paz La Paz-Cabo San Lucas	29,297	Urban and tourism Development Extensive cattle Raising Grazing land Forestry Deforestation
Loreto	Arroyo Frijol-Arroyo San Bruno Arroyo Mezquital-Arroyo Comondú Arroyo Venancio-Arroyo Salado Isla Coronados-Bahía La Paz	13,709	Urban and tourism Development Extensive cattle Raising Irrigation Agriculture Grazing land Deforestation
Los Cabos	Arroyo Caracol-Arroyo Candelaria La Paz-Cabo San Lucas	62,605	Urban and tourism Development Deforestation Extensive cattle Raising
Los Planes	Arroyo Caracol-Arroyo Candelaria La Paz-Cabo San Lucas	17,315	Urban and tourism Development Extensive cattle Raising Irrigation Agriculture Forestry
Santo Domingo	Arroyo Venancio-Arroyo Salado	70,182.30	Forestry Extensive cattle Raising Irrigation Agriculture
Todos Santos	Arroyo Caracol-Arroyo Candelaria La Paz-Cabo San Lucas	71,693	Urban and tourism Development Irrigation Agriculture Grazing land Extensive cattle Raising Forestry
Vizcaíno	Lago San Ignacio-Arroyo San Raymundo San Miguel-Arroyo del Vigía	5,355	Irrigation Agriculture Extensive cattle Raising Deforestation
	Total	**270,157**	

a methodological framework that allowed to identify the months of August to October as the dates on which the vegetation index for this arid region shows more contrasts. This allowed us to detect major changes in land-use change and identify areas subject to soil degradation through the loss of vegetation cover at a large scale. The analysis of the NOAA-AVHRR 1 km images allowed us to delineate areas with significant VI changes in greater detail.

We recognize seven critical areas with significant changes in their VI between 1990 and 2000 (see Table 3):

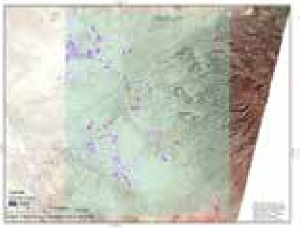
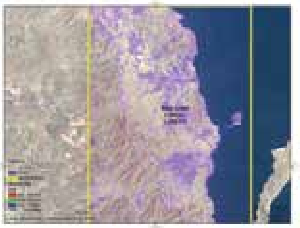
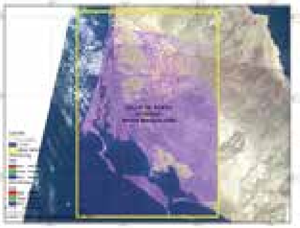
Los Cabos has the highest degree of variation in VI and thus presents the fastest degradation. Its rapidly-growing population, the growing demands for land from both, tourism and real estate, as well as other associated activities such as livestock ranching, agriculture, and forestry, are the main elements of degradation of the existing vegetation. The most affected vegetation types are the sarcocaulescent shrubland and the tropical deciduous forests of the lowland slopes.

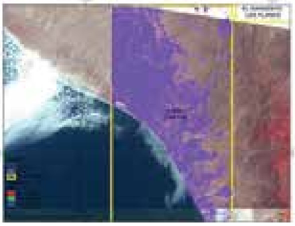
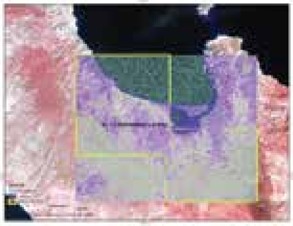
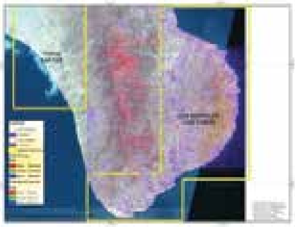
Santo Domingo is a prime example of the areas that have been affected by loss of natural vegetation driven by the opening new areas to agriculture. Currently clearing of new areas has been largely reduced and in parts halted by the exhaustion of the aquifer and the lack of good quality water for agriculture. The area, however, still harbors extensive grazing of the desert ranges and cutting of desert trees such as mesquite to make charcoal for the urban markets. These activities affect the lowland areas, valleys, and arroyos, where species such as mesquites (*Prosopis* spp.) are cut for their wood.

La Paz. In this region ranching and urban development (driven largely by tourism and the real estate market) are the main drivers of land-use change, coupled with deforestation driven by irrigation agriculture, and wood cutting for urban supply of materials and fuels. These activities focus mainly on the sarcocaulescent shrublands and on formations of giant columnar cacti. Other elements that affect this area are the roads and power lines that increase the fragmentation of wild lands in areas close to roads or to urban developments (Trombulak and Frissell 2000, Nellemann 2001, Arriaga *et al.* 2004, Arriaga 2009).

Todos Santos is the region with the largest proportion of the area with some form of soil degradation. The rapid increase in tourism and the ensuing demand for urban real estate in recent years have been intense drivers of land-use change, coupled with historic activities of agriculture and cattle ranching that have continued over generations.

TABLE 3. Synthesis of sites and main activities and vegetation affected.

Site	Vizcaíno (Villa Alberto Alvarado)	
Total degraded area	5,355 ha	
Geographic reference coordinates	27°30'N, 113°30'W	
Main activities / land use	Agriculture Extensive cattle ranching Forestry	
Affected native vegetation and previous land-use	Microphyllous desert shrubland Halophytic vegetation Irrigation agriculture	
Site	Loreto (San Juan Londó-Loreto)	
Total degraded area	13,709 ha	
Geographic reference coordinates	26°00'N, 111°30'W	
Main activities / land use	Irrigation Agriculture Extensive cattle raising Grazing land	
Affected native vegetation and previous land-use	Sarcocaulescent shrubland	
	Mesquite forest	
	Grazing land	
	Irrigation agriculture	
Site	Santo Domingo (Valle de Santo Domingo-Bahía Magdalena)	
Total degraded area	70,182 ha	
Geographic reference coordinates	25°00'N, 112°00'W	
Main activities / previous land use	Agriculture Extensive cattle raising Forestry	
Affected native vegetation and previous land-use	Mangrove forest Sarcocaulescent shrubland Crassicaulescent shrubland Irrigation agriculture	

Site	Todos Santos	
Total degrated area	71,693 ha	
Geographic reference coordinates	23°30’N, 110°15’W	
Main activities / land use	Agriculture Extensive cattle raising Forestry	
Affected native vegetation and previous land-use	Sarcocaulescent shrubland Crassicaulescent shrubland Grazing land Irrigation agriculture	
Site	**La Paz (El Centenario-La Paz)**	
Total degrated area	29,297 ha	
Geographic reference coordinates	24°00’N, 110°30’W	
Main activities / land use	Agriculture Extensive cattle raising Forestry Urban development	
Affected native vegetation and previous land-use	Sarcocaulescent shrubland Crassicaulescent shrubland Irrigation agriculture Urban development	
Site	**Los Cabos (Los Barriles-Los Cabos)**	
Total degrated area	62,605 ha	
Geographic reference coordinates	24°00’N, 110°30’W	
Main activities / land use	Agriculture Extensive cattle raising Forestry Urban development	
Affected native vegetation and previous land-use	Sarcocaulescent shrubland Tropical deciduous forest Irrigation agriculture Grazing land	

In recent years, Los Planes has established itself as a prime tourist destination for fishermen and people that practice water sports, and, as a result, deforestation has increased to give rise to real estate developments in the area. At the same time, historic ranching and irrigation agriculture have continued and even grown, largely to supply the booming local markets.

Loreto includes several types of land-use pressures: There is deforestation of the coastal Gulf shrubland, the presence of cattle ranching in the western portion of the town of Loreto and the basin of San Juan Londó, and different places that have been cleared for agriculture and then abandoned because of the decline of the aquifers and the enforcement of regulations for water extraction.

The large coastal plains of El Vizcaíno stand out as an area greatly affected by land-use change. During the last decades this area has been subject to growing demands from both desert agriculture and ranching, with the clearing of large tracts of land for irrigation from the rapidly-dwindling aquifer. Communication channels such as roads and power lines are also important factors of fragmentation of plant communities, mostly affecting the halophytic vegetation of the coastal plains and the inland desert scrub.

The considerations to select the analyzed areas as critical took into account as first element the variations in vegetation indices NDVI. The limits proposed in this paper are based on a regular polygon area, and represent a first approximation to the location of the areas of greatest VI change, according to the methodology employed. The quality of information provided by the analysis was derived from sensors of low and medium resolution (NOAA-AVHRR 1000m and Landsat ETM 30m respectively). Future projects following-up on these results should consider an analysis of greater detail in scale and spatial resolution of degraded areas.

In conclusion, although Baja California Sur is the most isolated and least populated State of Mexico, the level of degradation that occurs in these seven priority areas is alarming, having reached over 270.000 ha in only 10 years. This underscores the growing needs for management plans and environmentally friendly practices, and emphasizes the urgency of creating a sustainable culture that ensures the preservation of natural resources for future generations.

5. RECOMMENDATIONS

Although the Baja California Sur is the State with the most land area under environmental protection in Mexico, there are widespread conditions that promote the loss of vegetation cover and the rapid deterioration of the soil, seriously affecting ecosystem health in the region. Among the recommended actions to implement to stop this degradation process are:

1. Halt deforestation. This is a main priority, it is urgent to stop new permits aimed at:

a) New urban development's outside of the urban area
b) New agriculture areas
c) New forestry permits

2. Develop Land Planning (*Ordenamiento Ecológico*) studies for each basin in order to establish the types, locations and intensities of new productive activities allowed in each area as well as sites required for the conservation of natural resources.

3. It is urgent to minimize and restrict the impact ranching, opting for alternatives that allow a more sustainable consumption of natural resources and constrain grazing to animal densities in accord to the limited carrying capacity of the desert ranges.

4. Develop reforestation programs using native species to reverse the damage caused by natural and anthropogenic erosion. Such species should be produced in nurseries, including in their production modern technologies such as tissue culture techniques and bio-fertilization with symbiotic microorganisms.

5. Last but not least, the development of training and awareness programs that ensure community practices that are respectful with the natural resources are of critical importance in this still unique part of Mexico.

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PESTICIDES, HEAVY METALS, AND ARSENIC LEVELS IN COASTAL NORTHWESTERN MEXICO

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Over 40 studies from the published literature and data available from government agencies were gathered and reviewed in an effort to collect information on the environmental conditions on the coasts of northwestern Mexico with respect to pollution caused by heavy metals, arsenic and organochlorine y organophosphate pesticides in water, sediments and biota. Generally speaking, the amount of information is scarce and not up-to-date, as studies are localized and were conducted in diverse matrixes with significant spatial and temporal variations using non-standardized analytical methodologies at the national and international levels; circumstances that impede making any meaningful comparisons of the observed results. Several studies of contamination in biota were carried out on species characterized by high mobility (birds, marine mammals, reptiles) so the information is inadequate for evaluations on a regional scale. The most frequent organic pollutants detected were DDT and its metabolites, DDD and DDE, as well as lindane, two compounds whose use is currently banned or restricted. The presence of DDE in various animal species suggests recent utilization of DDT, though at lower levels than before its use was prohibited. Pesticide levels reported in turtles, whales and sea lions from the Gulf of California are significantly lower than those detected in other regions (the US, Mediterranean Sea, Gulf of Mexico). Due to their toxicity, some of the chemical compounds detected are covered by the Stockholm Convention. Studies conducted in coastal lagoons in the states of Sinaloa and Sonora (important agricultural regions) that analyzed water, sediments, fish, oysters and wild and cultivated shrimp detected such organochlorine pesticides as DDT and its metabolites, lindane, dieldrin, chlordane, oxychlordane, heptachlor, heptachlor epoxide, endosulfan, endrin and endosulfan phosphate, as well as 6 of the 19 organophosphate pesticides

included on the European Economic Community's priority list: demeton, dimethoate, disulfoton, ethyl parathion (banned for all uses in Mexico), methyl parathion, and malathion, as well as phorate sulfoxide (restricted in Mexico). Analyses in birds, whales, sea lions and turtles detected the presence of DDT and the metabolites hexachloro cyclohexane, dieldrin, aldrin, endosulfan, lindane, chlordane, oxychlordane, heptachlor epoxide, endosulfan and endrin. High levels of cadmium and lead were found in plants and animals that exceeded the allowable limits determined by the US Food and Drug Administration, but arsenic and mercury were not reported in high concentrations.

1. INTRODUCTION

Over the past 30 years, ocean pollution has become a subject of increasing international concern. The marine environment is being severely affected by chemical substances of both anthropogenic—residual urban, industrial and agricultural waters—and natural origin (primarily geological weathering). Terrestrial activities cause at least 80% of this pollution, which reaches the coast through such processes as surface runoff and groundwater seepage, as well as from the atmosphere. As the capacity of coastal areas to assimilate or disperse these contaminants is limited, they cause significant environmental deterioration that affects natural ecosystems (Colborn *et al.* 1993, Fry 1995, Heeren *et al.* 2003, Depledge and Galloway 2005).

Upon reaching the ocean, these contaminants mix directly with the water column, migrate with currents, or settle on the sea floor, where they may subsequently be absorbed into the food chain by bottom-feeders, or reintroduced into the water column by upwelling currents. Whatever their mechanisms of dispersion and transmission, pollutants accumulate in biota through the food chain and, in some cases, reach humans through consumption of contaminated marine products (Escobar J. 2002, Alavanja *et al.* 2004). With regard to the effects induced by chemical substances, the phenomena of residue transference and magnification through the trophic chain are described repeatedly and judged to constitute the principal risk for the environment and the health conditions of populations both wild and human (Colborn *et al.* 1993, Fry 1995, Heeren *et al.* 2003, Alavanja *et al.* 2004, Depledge and Galloway 2005). These compounds can alter various biological functions or processes, including reproductive cycles and development, while also inducing hormonal, neurological or metabolic dysfunctions (Colborn *et al.* 1993, Fry 1995, Soengas *et al.* 1997). Moreover, according to the International Agency for Cancer Research (IACR), the European Union (EU), and the US Environmental Protection Agency (EPA), some are known, or suspected, cancer-causing agents in humans. One French study of farmers afflicted with Parkinson's disease estimated that exposure to lindane and DDT doubled the risk of contracting this illness (Elbaz *et al.* 2009).

Generally, ingested metallic elements are not readily absorbed; however, the organic compounds they form may have long half-lives in large herbivores and carnivores. Even at moderate exposures such organic metallic compounds can have detrimental effects over time, depending on the ingredients and chemical composition of the foods consumed.

The chapter reviews the information available in the scientific literature and from government sources on problems of environmental pollution due to pesticides, heavy metals and arsenic in northwestern Mexico: *i.e.*, the Peninsula of Baja California, Sonora, Sinaloa and Nayarit (see Figure 1).

2. PESTICIDE USE IN MEXICO

More than 800 chemicals are used to control urban, woodland and agricultural plagues, including organochlorine (OC) and organophosphorus compounds (OP), carbamates and pyrethroids. In Mexico, information on pesticide use as it relates to both public health and agricultural activities is incongruent. For example, the report issued by Mexico's Institute for Environmental Health and Work (ISAT) on the use of DDT in Mexico and Central America, commissioned by the Panamerican Health Organization and conducted in 2001, states that the country banned all use of DDT in agriculture in 1991 and in public health (where it was used to combat malaria) in 2000. However, Gonzalez-Farías *et al.* (2002) report that although OC were officially banned, their use was still permitted under certain conditions or restrictions: for example, dichlorodiphenyl-trichloroethane **(**DDT) to control diseases transmitted by mosquitoes; chlordane, dicofol and methoxychlor for insect pests that affect specific crops; and endosulfan for pests on coffee plantations.DDT is found in the environment in several isomeric forms: *p,p*'-DDT, *o,p*'-DDT and *m,p*'-DDT, that contain residues that are even more toxic, such as dichlorodiphenyl-dichloroethylene (DDE) and dichlorodiphenyl-dichloroethane (DDD), and may be present in diverse forms, including *p,p*'-DDE, *o,p*'-DDE, *p,p*'-DDD and *o,p*'-DDD (US-EPA 1980).

An extremely toxic substance, hexachlorocyclohexane (HCH), and its isomer, γ -HCH (or lindane) fit the criteria for inclusion on the list of Persistent Organic Contaminants for future elimination worldwide, according to the Stockholm Convention (2009). As a result, 37 countries have severely restricted its use. But in Mexico lindane is still utilized in agriculture and in treatments for pediculosis and scabies. The federal government estimates that the volume authorized for importation into

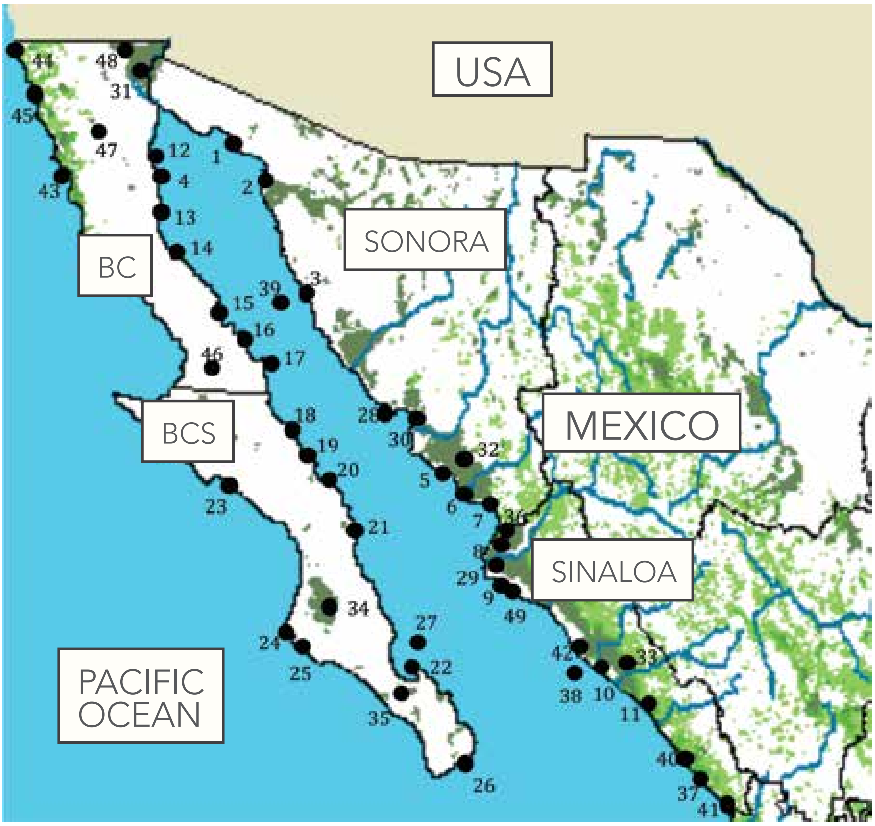

FIGURE 1. Sites where environmental pollutants have been studied in Northern Mexico (Bi = Birds, FS = Farmed shrimp, Fi = Fish, Li = Sea lions, Mu = Mussels, Oy = Oysters, Se = Sediments, Tu = Turtles, Wa = Water, Wh = Whales, and WS = Wild shrimp): BC = Baja California, BCS = Baja California Sur. 1. Estero Morua (Oy), 2. Bahía San Jorge (Oy, Bi), 3. Bahía Kino (Oy), 4. Bahía de Guaymas (Oy), 5. Riito (Oy), 6. Huatabampito (Oy), 7. Bacorehuis (Oy, Se), 8. Bahía Lechuguita (Oy), 9. Bahía Navachiste (Oy), 10. Bahía Altata (Oy), 10. Ensenada del Pabellon (Se), 11. Bahía Ceuta (Oy, Se, Wa), 12. Punta Estrella (Mu), 13. Puertecitos (Mu), 14. Bahía de San Luis Gonzaga (Mu), 15. Bahía de los Ángeles (Mu), 16. San Rafael (Mu), 17. San Francisquito (Mu), 18. Santa Rosalia (Mu), 19. Estero Lucas (Mu), 20. Mulegé (Mu), 21. Bahía de La Paz (Tu), 21. Nopoló (Mu), 22. Bahía de La Paz (Mu), 23. Punta Abreojos (Tu), 24. Barra San Lázaro (Tu), 25. Bahía Magdalena (Tu), 26. (Tu) Los Cabos, 27. Los Islotes (Li), 28. Isla Nolasco (Li), 29. Bahía Ohuira (Se, Wa, WS), 30. Atanasia Santo Domingo (FS), 31. Valle de Mexicali (Bi), 32. Valle del Yaquí (Bi), 33. Valle de Culiacán (Bi), 34. Valle de Santo Domingo (Bi), 35. Chametla (Bi), 36. El Colorado (Fi), 37. Laguna Huizache Caimanero (Fi, Wa), 38. Etchoropo Laguna Yameto (Fi), 39. Center of the Gulf of California (Wh), 40. Estero de Urias (Wa), 41. Estero de Teacapan (Wa), 42. Bahía de Santa María (Wa), 43. Bahía, 44. Coronado (Bi), 45. Todos Santos (Bi), 46. San Martín (Bi), 47. San Pedro Mártir (Bi), 48. San Idelfonso (Bi), 49. Farallón San Ignacio (Bi).

the country from 1997 to 2002 exceeded 900,000 kg. Indeed, it has admitted, first, that it has no precise information on production volumes of this substance and, second, that due to budgetary limitations it does not measure the presence of DDT in the environment, workplace exposures, or the numbers of patients with pediculosis or mange (Patiño and Rodríguez 2005). According to Ecobichon (2001) and Goldman and Tran (2002), the high risk from pesticide exposure in Mexico is a result of several specific sources:

Authorized use of pesticides that are banned in other countries due to high toxicity (CICOPLAFEST 1994); in some cases because expired patents or simplified manufacturing procedures result in substantially lower costs.

Continued use of pesticides despite the fact that they are prohibited or restricted by CICOPLAFEST (1998).

Mexico's extensive areas of tropical or subtropical climates present complications that were not anticipated in the original applications and quantities of pesticide use.

The proper use, control and handling of pesticides are not commonly practiced.

There is little or no governmental oversight of imports, registration, marketing, application procedures, worker training and disposal of contaminated waste.

Legal regulation and monitoring of pesticides released into the atmosphere is inadequate.

The generally low educational level of the population, especially ignorance of the dangers involved in using and storing pesticides, and health hazards from exposure.

3. PRESENCE OF PESTICIDES IN BIOTA

3.1. Birds

One effect of organochlorine pesticides (OC) in birds is that it thins the shells of their eggs, thus altering their reproductive success. Historically, northwestern Mexico has hosted important breeding colonies of marine birds. Since the 1970s, however, high levels of DDT and DDE have been detected and associated with problems observed in the reproduction of brown pelicans (*Pelecanus occidentalis*) (Jehl 1973, Anderson *et al.* 1975), and double-crested cormorants (*Phalacrocorax auritus*) (Gress *et al.* 1973). Mora and Anderson (1991) confirmed the presence of organochlorine residues in 8 bird species in agricultural zones of Mexicali, Sinaloa and Sonora. DDE was found in all samples collected and at higher levels than other OC. Mean DDE concentrations varied from 0.04 μg/g in mourning doves (*Zenaida macroura*) to 5.05 μg/g in double-crested cormorants. HCH was detected in 95% of samples, but at lower levels than DDE. Other OC, such as DDT, DDD, dieldrin, oxychlordane, heptachlor epoxide, endosulfan and endrin, were found at lower levels and less frequently (see Table 1). Mellink *et al.* (2009) analyzed the presence of OC and

TABLE 1. Organochlorine concentrations (ppm) in birds from Northwest Mexico (Mora and Anderson, 1991). BC = Baja California; ND = Not detected.

Species	Location	HCB	HCH	DDE	Dieldrin	DDT
DC cormorant	Mexicali; BC	0.006	0.018	11.46	0.026	0.018
	Yaqui, Sonora	0.006	0.015	0.82	0.025	0.007
	Culiacán, Sinaloa	ND	0.043	5.05	0.026	0.023
Ol cormorant	Culiacán, Sinaloa	0.012	0.065	3.77	0.025	0.02
Cattle egret	Mexicali, BC	0.012	0.009	1.99	0.022	0.016
	Yaqui, Sonora	0.005	0.007	0.75	0.043	0.02
	Culiacán, Sinaloa	ND	0.018	0.27	0.012	0.008
GT grackle	Mexicali, BC	0.006	0.007	3.06	0.007	0.009
	Yaqui, Sonora	0.005	0.008	1.93	0.001	0.012
	Culiacán, Sinaloa	0.029	0.011	0.46	0.012	ND
RW blackbird	Mexicali, BC	0.006	0.008	1.68	0.009	0.008
Mourning dove	Mexicali, BC	ND	0.007	0.04	ND	0.019
	Yaqui, Sonora	ND	0.01	0.03	0.009	ND
	Culiacán, Sinaloa	0.015	0.025	0.06	0.006	ND
WW dove	Yaqui, Sonora	ND	0.009	0.02	ND	ND
	Culiacán, Sinaloa	0.019	0.013	0.04	0.009	ND

TABLE 2. Mean DDE (ppm), eggshell thickness (mm) and eggs volume (cc) of brown booby (*Sula leucogaster*) eggs along of islands from California Gulf (Mellink *et al.*, 2009).

Colony	DDE	Thickness	Volume
San Jorge (Sonora)	0.0533	0.5434	52.402
San Pedro Mártir (BC)	0.0529	0.494	50.595
San Ildefonso (BC)	0.0344	0.4996	51.897
Farallón de San Ignacio (Sinaloa)	—	0.5133	48.232

eggshell thickness in colonies of *Sula leucogaster* at 4 sites in the Gulf of California (see Table 2) and found DDE in every sample examined, though in concentrations insufficient to cause thinning of the eggshells. Rivera-Rodríguez (2007) detected low concentrations of OC in a pristine population of osprey hatchlings *(Pandion haliaetus)* located 80 km from an agricultural plain in Laguna de San Ignacio, Baja California (see Table 3). The concentrations recorded were lower (0.0002-6.856 parts

TABLE 3. Pesticides incidence (%) in birds from Baja California Sur, Mexico (Rivera-Rodríguez, 2007). N = Number of birds tested; HCH = Isomers of lindane; HC = Heptachlor; DDE = Isomer of DDT; ESI = Endosulphane I.

Species	N	α-HCH	β-HCH	δ-HCH	γ-HCH	HC	AD	ED	DE	DDE	ESI
Columbina passerina	49	61	57	55	47	88	82	73	100	100	71
Melanerpes uropygialis	5	33	0	0	0	67	67	67	100	100	100
Myarchus cinerascens	5	20	20	0	20	60	40	40	100	100	60
Toxostoma cinereum	6	50	50	17	50	50	33	83	100	100	100
Icterus cucullatus	9	67	78	78	44	89	67	78	100	100	78
Falco sparverius	3	67	100	100	67	100	100	67	100	100	100
Picoides scalaris	5	0	0	0	0	100	80	100	100	100	100
Colapses auratus	2	100	50	50	50	50	50	100	100	100	50
C. brunneicapillus	13	50	43	50	43	79	71	100	100	100	79
Mimus polyglottos	23	61	48	57	43	91	74	83	100	100	83
Molothrus ater	4	75	50	75	50	75	75	75	100	100	100
Icterus parisorum	7	38	38	38	38	75	75	75	100	100	100
Passer domesticus	4	50	50	50	50	75	50	75	100	100	100
Callipepla californica	4	75	75	75	50	75	50	75	100	100	100
Zenaida asiatica	2	100	100	100	50	100	100	50	100	100	100
Zenaida macroura	6	50	50	50	50	100	100	100	100	100	75
Sturnella neglecta	4	100	100	75	100	75	100	100	100	100	75
Carpodactus mexicanus	10	90	90	90	90	90	90	90	100	100	80

per billion), than those reported in other studies and considered a threat to the survival of the species. In effect, surveys conducted by Danemann in 1992 (1994), and Rodríguez-Estrella *et al.* in 1998, 2002 and 2003 (2006) suggest that reproduction of this species has not varied.

In summary, data on the presence of pesticides in birds in northwestern Mexico is limited and shows no clear pattern. The mobility of some species makes it impossible to identify the precise origin of the pesticides found. Also, the reproductive success of some species—eg., *Pelecanus occidentalis*—that seemed to have been altered by ingesting OC apparently returned to earlier levels once the indiscriminate use of DDT was controlled in 1972 (Jehl 1984, Anderson *et al.* 1996). However, studies of diverse species carried out between 1981 and 2010 continued to detect a metabolite of DDT: DDE. This metabolite breaks down quickly, but its mere presence indicates that this dangerous pesticide is still being utilized despite the ban, though perhaps at lower concentrations, as there have been no reports of variations in the reproduction of species like the osprey since 1992.

3.2. Turtles

Though the eastern and western coasts of Baja California are considered among the main feeding and breeding areas of *Chelonia mydas, Lepidochelys olivacea* and *Caretta caretta*, there are only two documented studies on the presence of pesticides in turtles collected in this region (Gardner *et al.* 2003, Juárez-Cerón 2004). These authors detected the presence of significant concentrations of DDT and its metabolites in the organisms they studied, though levels were lower than those recorded in other sites (Mediterranean Sea, Atlantic and Pacific Ocean). Also found were levels of other OC, including dieldrin, aldrin, endosulfan, lindane and chlordane (see Table 4), though identifying the sources of these contaminants is difficult. Turtles are long-living, relatively large animals that occupy different places in the food chain and migrate from a few kilometers to transoceanic journeys that expose them to numerous potential sources of pollutants that may accumulate at the high end of the food chain. As agriculture in Baja California Sur is not extensively developed, the contaminants detected in wildlife from its coasts have been attributed to DDT residues carried by ocean currents and marine upwellings from California (US).

3.3. Marine mammals

In marine mammals, exposure to OC pesticides produces alterations in their immunological and reproductive systems (Niño-Torres *et al.* 2009). In cetaceans, persistent compounds accumulate in fatty tissues and affect the organisms' health by reducing their capacity to disintoxicate their lipid reserves. The compounds most frequently

TABLE 4. Comparison of concentrations (ng g^{-1}) of the most common pesticides in marine turtles in the world (Juárez-Cerón, 2004). (1) Rybitski *et al.*,1995; (2) Mckenzie *et al.*,1999; (3) Juárez-Cerón, 2004; (4) Aguirre *et al.*, 1994; (5) Gardner *et al.*, 2003;(6) Lake *et al.* 1994.. ΣDDT = o.p.'-DDT, o.p.'-DDE, o.p.'-DDD, p.p.'-DDT, p.p.'-DDE, p.p.'-DDD; DD = Dieldrin; CD = Chlordane. BCS = Baja California Sur (Mexico). ND = Not detected. NR = Not reported.

Species	Location	ΣDDT	DDE	DD	CD	Year
Caretta caretta	Atlantic Ocean (1)	121	108	NR	NR	1991
	Mediterranean Sea (2)	508	491	5	18	1994–1995
	BCS coast (3)	45	44	ND	34	2001–2003
	BCS coast (5)	ND	NR	ND	ND	2003
Chelonia mydas	Mediterranean Sea (2)	9	NR	3	NR	1995–1996
	Hawaii (4)	ND	ND	ND	ND	1994
	BCS coast (3)	2	2	ND	23	2001–2003
	BCS coast (5)	ND	NR	5	ND	2003
Lepidochelys olivacea	BCS coast (3)	15	15	ND	24	2001–2003
	BCS coast (5)	18–May	NR	7	Aug–45	2003
Lepidochelys kempii	Atlantic Ocean (6)	454	386	NR	NR	1985
	Atlantic Ocean (6)	261	232	NR	NR	1989
	Atlantic Ocean (1)	288	176	NR	NR	1991

detected are DDT and its metabolites, DDD and DDE. Because the most important, and rapid, product of the breakdown of DDT is the isomer p.p'-DDE, it is calculated in relation to total p.p'-DDE/DDTs to determine the recent entry of DDT into an organism from the environment (Borrel *et al.* 1995, ATSDR 2002). Studies conducted in blue whales from the Gulf of California (Balaenoptera musculus) detected maximum levels of total DDTs on the order of 2833 ng/g-1 of lipids, of which 75% corresponded to p.p'-DDE (Flores Lozano 2006). In 2004, Valdés and Márquez detected total DDT concentrations of 4510 ng/g-1 of lipids, and a percentage of p.p'-DDE of 71% in this species. The sources of this contamination are hard to ascertain. The blue whales seen in the Gulf of California come from high latitudes and migrate in winter to Mexican waters to give birth, breastfeed their young and feed. From August to early October, the whales feed primarily in the coastal area of central California, US, where they could be contaminated. However, Niño-Torres *et al.* (2010) suggest that the most important source of the pollutants found in whales is

TABLE 5. ΣDDT, ΣHCH, and ΣCHLOR concentrations (mean, ng g^{-1} lipid weight) in fin whales *Balaenoptera physalus* (Niño-Torres *et al.*, 2010). (1) Gauthier *et al.* 1997; (2) Hobbs *et al.* 2001; (3) Marsili and Focardi, 1997; (4) Marsili *et al.* 1998; (5) Niño-Torres *et al.* 2010.

Location	ΣDDT	ΣHCH	ΣCHLOR
Northwestern Atlantic (1)	3,800	210	570
Northwestern Atlantic (2)	26,900	165	1,500
Mediterranean Sea (3)	5,700	—	—
Mediterranean Sea (4)	1,770	—	—
Gulf of California (5)	1,200	24	21

agricultural activity in Sonora and Sinaloa, where 40% of Mexico's national production takes place, and not contaminants carried down from the US by atmospheric and marine currents.

There is only one report with data on concentrations of different classes of OC in the fatty tissues of *Balaenoptera physalus* whales, a year-round resident of the Gulf of California and one of this species' most isolated populations (Niño-Torres *et al.* 2010). The rank order of OC was total DDTs (maximum values: 2400 ng g^{-1} lipid weight), and the most abundant OC pesticide measured was p.p'-DDE, which represented 60% of total DDTs. These authors found this population to be generally clean (see Table 5) compared to other marine mammal species, or fin whale populations from other regions (*e.g.*, Mediterranean Sea, Atlantic Ocean).

The California sea lion (*Zalophus californianus*) is the most abundant species among the pinnipeds present in Mexico. There are two populations, one of which inhabits the Gulf of California. Though its migratory behavior is still unknown, studies have established that 35% of males remain in the rookeries year-round (Zavala 1990). The second colony is found on the Pacific coasts of Baja California and migrates in search of food along the coasts of the US and Canada, where it stays until the onset of the mating season (Antonelis *et al.* 1990). Niño-Torres *et al.* (2009) conducted a study of the sea lions from the Gulf of California in which they reported finding several classes of OC compounds (see Table 6). The most abundant OC measured was the DDT metabolite p.p'-DDE, which accounted for more than 85% of total DDTs (maximum value 3400 ng g^{-1} lipid weight). Concentrations of the same order of magnitude were reported in 2006 by Del Toro *et al.* for organisms that inhabit the Pacific coast of Baja California. In contrast, the concentrations observed were up to two orders of magnitude lower than the values reported previously by Le Boeuf (2002), Kannan *et al.* (2004), Ylitalo *et al.* (2005), and Greig *et al.* (2007) in samples

TABLE 6. ΣDDT, ΣHCH, and ΣCHLOR concentration ranges (ng g^{-1} lipid weight) in California sea lions *Zalophus californianus*. ΣDDTs=o,p'-DDE,¨p,p'DDE, o.p'-DDT, p,p'-DDT,o,p¨-DDD, and p,p'-DDD; ΣHCHs= α -HCH, β -HCH, γ -HCH, δ -HCH; ΣCHLORs= β -chlordane, γ -chlordane, heptachlor, heptachlor epoxide <LOQ-69, less than the limit of quantification. NA = Not analyzed).1) Niño-Torres *et al.*, 2009, (2) Greig *et al.*, 2007. BCS=Baja California Sur

Location	ΣDDT	ΣHCH	ΣCHLOR
Los Islotes, BCS (1)	1,000–5,200	16–110	25–100
San Pedro Nolasco Island, Sinaloa (1)	1,500–7,700	18–120	<LOQ–69
California Coast, USA (2)	4,600–120,000	NA	NA

collected from whales in coastal areas of the US. The range of total p, p'-DDE/DDT values found in studies from the Gulf of California is similar to that seen in areas where DDT has not been used for the past 30 years (Niño-Torres *et al.* 2009).

3.4. Fish

Pesticide contamination in fish has not been extensively studied in northwestern Mexico. Rosales *et al.* (1983) examined concentrations of OC in striped mullet, white mullet, mackerel and flounder in Laguna Yavaros, Sonora, and the Huizache-Caimanero coastal lagoons of Sinaloa, which receive runoff from intensive agro-ecosystems. DDT and dieldrin residues were lower than the range of values reported in the literature and were below the accepted standards for human health (500 ng g^{-1} wet weight for DDT, and 100 ng g^{-1} wet weight for dieldrin). In 2002, Bravo-Garzón detected the presence of hexachlorobenzene (9.5 at 24 µg g^{-1}) and 4'4 DDE (1.5 at 6.7 µg g^{-1}) in liver samples from *Mugil cephallus* monitored in Bahía El Colorado (Sinaloa) and Bahía de La Paz (Baja California Sur). This highly-toxic substance is produced by industrial and natural combustion processes, and accumulates in the fatty tissues of living organisms. This author also observed inhibitions of the order of 27% in acetylcholinesterase activity in the fish collected. Measurements of this enzyme's activity are included as one of the biomarkers in environmental monitoring programs designed to detect the presence of organophosphate and carbamate pesticides (Sturm *et al.* 1999, Bretaud *et al.* 2000) that are difficult to detect analytically due to their rapid breakdown rates in the natural environment.

3.5. Wild and farmed shrimp

Galindo-Reyes (2000) found OC and OP pesticides in shrimp (*Penaeus* sp.) and the surrounding water and sediments in seven coastal zones in Sinaloa (Estero de

TABLE 7. Pesticides in wild shrimp (ng g^{-1}), water (ng L^{-1}), and sediments (ng g^{-1}) of Sinaloa, Mexico (Galindo-Reyes 1999b). *Higher levels than the limits allowed in water by Mexican law. EX = Epoxide, ΣDDT = DDT and its metabolites, ES = Endosulphane, HC = Heptachlor, MP = Methyl parathion, DD = Dieldrin, CD = Chlordane, AD = Aldrin, ED = Endrin.

Location	Sample	α HCH	EX	ΣDDT	ES	HC	MP	DD	CD	AD	ED
Estero Urias	Shrimp	0.15	0.08	0.05	210	126	114	ND	ND	ND	ND
Estero Urias	Water	0.79*	ND	3.27*	ND	4.28*	ND	ND	ND	1*	1*
Bahía Ohuira	Water	2	0.23	8	73	ND	11	19	ND	ND	ND
Bahía Ohuira	Sediment	ND	43	ND	155	60	98	51	ND	ND	ND
Bahía Ohuira	Shrimp	132	ND	ND	210	126	113	ND	112	ND	ND
Huizache-Caimanero	Water	3*	ND	ND	ND	ND	0.21*	ND	ND	ND	ND

Urias, Bahía de Ceuta, Bahía de Ohuira and Topolobampo, Laguna de Huizache-Caimanero, Estero de Teacapan, Bahía de Santa Maria, and Ensenada del Pabellón). Table 7 shows only the highest levels of the pollutants registered during monitoring in 1990, 1991 and 1997. The most polluted site was Estero de Urias. OC appear more often than OP, likely because the former are more persistent in aquatic systems. For example, while DDT can last as long as 35 years, methyl parathion disappears in just 4–7 weeks. The highest incidence occurs during the summer months when rainfall carries sediments and pesticides towards the coast.

Osuna-Flores and Riva (2002) measured pesticide concentrations in shrimp, water and sediments in Sinaloa (Bahía de Ohuira) and found 6 of the 19 organophosphate compounds cited in the European Economic Community's priority list: demeton, dimethoate, disulfoton, ethyl parathion, methyl parathion and malathion. Of the organophosphate compounds found in this study, only the pesticide phorate is of restricted use, while the ethyl parathion compound is totally banned in Mexico (INE 1996).

Based on the presence of organophosphate pesticides, we can infer that while the compounds demeton (40%) and phorate sulfoxide (33%) are those most commonly

TABLE 8. Pesticide concentrations in farmed shrimp (ng g^{-1}), and sediments (ppm) from the estuary La Anastasia-Santo Domingo in Cajeme, Sonora (Burgos-Hernández *et al.*, 2005). CPF = Chlorpyrifos, MLT = Malathion, PRT = Parathion, ED = Endrin, DD = Dieldrin, γ HCH = Lindane.

Matrix	CPF	4'-4-DDD	MLT	PRT	ED	DD	γ HCH
Sediment	1.25–6.8	2.15	<0.5	<0.5	<0.5	<0.5	<0.5
Shrimp	>13	<0.4	35	12	<0.4	<0.4	<0.4

found in surface water, in sediments the compounds famphur (47%), demeton and chlorpyrifos (40%) show the highest incidences. The latter was determined to have the greatest presence in the organisms studied (50%). There are only a few reports on organophosphate pesticides that contain detailed information on aquatic systems indicating the presence of certain organophosphate compounds in surface water, such as methyl parathion (0.02–0.2 μg/L), dimethoate (0.06–0.6 μg/L), parathion (0.006–0.02 μg/L), malathion (0.007–01(g/L), disulfoton and famphur (0.01 and 0.04 μg/L, respectively). Findings in sediments were as follows: disulfoton (2.9–17.9 μg/g), parathion (<0.1 ng/g–0.02 μg/g) and chlorpyrifos (<0. 1ng/g–0.2 μg/g) (Readman *et al.* 1992, Galindo *et al.* 1997, Galindo *et al.* 1999a, 1999b). Studies with toxicological evaluations of organophosphate pesticides have proven that the compound chlorpyrifos is the most toxic substance for penaeid shrimp (Galindo *et al.* 1996, Osuna *et al.* 1997).

The Agiabampo-Bacorehuis-Jitzamuri lagoon complex in Sinaloa receives water from seven channels that irrigate 4604 farms. There, González-Farías *et al.* (2002) sampled sediments for pesticides and found high levels of heptachlor (49.08 ng g^{-1}), heptachlor epoxide (64.5 ng g^{-1}), DDT (51.56 ng g^{-1}), and HCH (30.36 ng g^{-1}). High concentrations of DDT, compared to its metabolites, DDE (0.49 ng g^{-1}) and DDD (12.95 ng g^{-1}), indicate that the former has not been broken down and strongly suggest that recent illegal applications have taken place, as these data are dissimilar to findings by CICOPLAFEST (1998) regarding the type of pesticides used in this area.

The highest levels of pesticides found in cultivated shrimp, water and sediments in Sonora's Laguna La Anastasia are shown in Table 8. Dieldrin, DDT and its metabolites, chlordane, and heptachlor were all detected in shrimp, though at levels below the standards set by the FDA and EPA in the US, which are 300 ng g^{-1} for dieldrin, 300 ng g^{-1} for heptachlor, 300 ng g^{-1} for chlordane, and 5,000 ng g^{-1} for DDT and its metabolites. However, there are reports that these levels are toxic in shrimp as they alter osmoregulation, glycogen synthesis, respiration rates, and cholinesterase activity.

Analyses of sediments, water and biota from the Altata-Ensenada del Pabellón lagoon complex in Sinaloa showed residues of OC and OP (Carvalho *et al.* 2002). For all pesticides, concentrations were higher in the sediments sampled near water discharge outlets from ponds and drainage channels from farmland. Among the OC, DDT and its metabolites had the highest values in sediments, followed by endosulfan and chlorpyrifos.

Sericano *et al.* (1990) sampled sediments and biota from the Gulf of California and found that DDT concentrations were lower than those of its metabolites, DDD and DDE; results that confirm that DDT use has been reduced. Concentrations ranged from 0.6–45 ng g^{-1} total DDT in sediments, which is below the levels detected in the Gulf of Mexico (range 0.02–3270 ng g^{-1}). Chlorpyrifos was the principal OP detected in those sediments (0.4–8 ng g^{-1}). There is no data available on the toxic effects of this compound in marine fauna, despite its relatively long stability in sediments (160 d). High concentrations of DDE (0.2–450 ng g^{-1}), dieldrin (2.5–13 ng g^{-1}), and endosulfan phosphate (3–530 ng g^{-1}) were found in mussels, oysters and fish (Carvalho *et al.* 2002).

3.6. Sentinel organisms

Mussels and oysters are used as quantitative biomarkers of pollution (Rittschof and McClellan-Green 2005). These mollusks have the ability to accumulate certain pollutants present in the environment where they live (including metals and hydrophobic organic contaminants). Numerous countries in Europe and the Americas have developed monitoring systems using this technique, under the generic name "Mussel Watch" (IFREMER 2011). Such systematic monitoring makes it possible to determine the tendencies of contaminants over time, while simultaneously assessing their effects on biota. In 2007–2008, Vázquez Boucard *et al.* 2008, implemented such a program based on the systematic monitoring of OC, OP and metals in the coastal waters of Sonora, Sinaloa and Nayarit, using the Pacific oyster, *Crassostrea gigas*, as the sentinel species. The oysters were kept in cages on the sea bed for a period of three months and placed precisely on the water inflow drains from 50 shrimp and oyster farms. Samples were collected monthly for a total of 18 months. Of the 22 compounds analyzed, the highest concentrations of OC detected (see Table 9) corresponded to lindane, with up to 72.5 ng g^{-1}; a level that produced genotoxic damage (Comet test) in exposed test organisms (Bigaud 2008). Anguiano-Vega *et al.* (2007) and Anguiano-Vega (2008) found that lindane affected four genes in *C. gigas*, reflected in differential kinetic expression (superoxide dismutase, ferritin, tumoral necrosis protein, and oxidizing stress SHG protein). Chemical analyses did not detect OP; however an assay of acetylcholinesterase activity in these oysters did find a strong

TABLE 9. Pesticides concentrations (ng g^{-1}) detected in sentinel organism *Crassostrea gigas* from coastal waters of Mexico (Vázquez-Boucard *et al.*, 2008). ES= Endosulphane; ED= Endrin. ND= Not detected.

State	Location	γ HCH	DDT	DDD	DDE	ED	ES I	ES II
Sonora	Estero Morua	ND	ND	ND	ND	ND	5.35	ND
	Bahía San Jorge	ND	ND	ND	ND	ND	ND	ND
	Bahía Kino	ND	ND	ND	ND	ND	ND	ND
	Bahía Guaymas	13.61	ND	ND	ND	ND	ND	ND
	Riito	72.50	ND	ND	1.54	ND	ND	2.48
	Huatabampito	ND	ND	ND	ND	ND	ND	ND
Sinaloa	Bahía Lechuguita	ND	ND	ND	ND	9.39	ND	ND
	Bacorehuis	44.48	ND	ND	ND	8.13	2.29	4.43
	Bahía Altata	ND	ND	ND	ND	ND	ND	ND
	Bahía Ceuta	ND	ND	ND	ND	ND	ND	1.45
	Bahía Navachiste	39.80	3.65	3.29	1.19	ND	1.62	1.38

inhibition in organisms from several locations; an inhibition from exposure to OP and carbamates that is amply documented in the literature (Ozmen 1999, Pfeifer *et al.* 2005). Though the method used to detect OP (at two different laboratories) is apparently unable to identify trace levels of this pollutant, the biological effects of this substance have been documented. It is worrisome that several unidentified peaks appear in chromatographic chemical analyses, because they might represent new molecules that have not yet been standardized for the methodology employed. With the exceptions of zinc and cadmium (Mexicans Norms), the concentrations of the other heavy metals studied (copper, nickel, lead) did not exceed allowable limits. Despite the significant levels of zinc detected in that study—and according to the criteria of alimentary innocuity as they relate to the presence of heavy metals—the maximum allowable limit for daily ingestion was exceeded only mildly and on but a few occasions. With respect to lindane and endosulfan, two highly toxic contaminants that were detected in very significant concentrations, there are no studies that allow us to determine the maximum tolerable daily ingestion in relation to alimentary innocuity in oysters cultivated in zones under environmental risk.

In 1987 and 1988, Gutiérrez-Galindo *et al.* (1992) monitored the horse mussel, *Modiolus capax*, as a pollutant biomarker for OC and OP pesticides along the east coast of the Baja California Peninsula. At that time, the most common OC in the waters of the Gulf of California was DDE (5.78–10, 3 ng g^{-1} dry weight). The most severely affected bays were Bahía de los Ángeles, Bahía de San Rafael, and Bahía de San Francisquito along the central coast of the Peninsula. Also present were lower concentrations of heptachlor epoxide, dieldrin, chlordane and endosulfan. Since the adjacent land is desert-like with low rainfall, the authors believe that the source of the DDE is located in the agricultural areas of Sinaloa and Sonora, runoff from which is carried across the Gulf of California by cold water currents, as described by Badan-Dangon *et al.* (1985).

4. HEAVY METALS AND METALLOIDS

Heavy metals and metalloids, common constituents of the earth's crust, are released continuously into the biosphere by volcanoes and the natural weathering of rocks, but numerous anthropogenic activities—including fuel combustion, industrial and urban sewage, and agricultural practices, among others—also produce heavy metals and metalloids. These are classified as pollutants when they exceed the levels judged as normal by the international guidelines of the World Health Organization, the US Food and Drug Administration, and the US Environmental Protection Agency, among others. This chapter considers only the chemical elements reported in high concentrations in coastal northwestern Mexico as they relate to those guidelines.

4.1. Lead

Lead and cadmium are the most widely studied pollutants in northwestern Mexico. Though found naturally in minerals like galena (PbS), lead is often considered an indicator of pollution from industrial sources and, especially, fossil fuel combustion (Cotter-Howells and Thornton 1991). The FDA (2003) established a limit of 7.5 µg Pb g^{-1} dry weight (or 1.5 µg Pb g^{-1} wet weight) in mollusks as safe for human consumption. Based on these limits, unsafe levels of this element have been reported in fauna from northern Mexico. For the Gulf of Santa Clara, Cadena-Cárdenas *et al.* (2009) report levels of approximately 9.6 µg Pb g^{-1} in white clams, *Chione californiensis*; while Méndez *et al.* (2006) detected concentrations of up to 7.8 µg Pb g^{-1} in the squalid callista clam, *Megapitaria squalid*, collected in an area north of Bahía de La Paz. In addition, Páez-Osuna *et al.* (1988) found lead in samples of *Mytelia strigata* at values up to 11.7 µg g^{-1}, almost double the limit set by the FDA (2003).

In a study conducted on the southeastern coast of the Gulf of California, Soto-Jiménez *et al.* (2008) reported average lead concentrations in the following aquatic fauna (all figures in µg g^{-1}): zooplankton (~32), mussels (2.3–3.9), oysters (1.9–7.9), snails (2.0–7.7), barnacles (0.1–18.5), fish (1.4–8.9), crabs (6.3–40.2), and polychaete (8.5–16.7). In that study, oysters, fish and crabs exceeded acceptable levels for human consumption. However, government standards for lead vary; for example, Mexico's Norm NOM 31SSA1-1993 allows a maximum of 1.0 μg Pb g^{-1}, while the FDA (2003) sets a maximum limit of 1.7 μg Pb g^{-1} (fresh wet weight).

Lead has also been quantified in marine mammals. In Laguna Ojo de Liebre on the Pacific side of the Baja California Peninsula, a kidney sample from the gray whale, *Eschrichtius robustus*, contained 31.6 μg Pb g^{-1} (De Luna and Rosales-Hoz 2004), five times above the highest concentration found a few years earlier by Méndez *et al.* (2002) in lung (4.4 μg Pb g^{-1}) and kidney tissues (6.12 μg Pb g^{-1}). According to Law *et al.* (1992), concentrations that exceed 4.0 μg g^{-1} indicate lead poisoning in marine mammals.

4.2. Cadmium

In mollusks, cadmium has frequently been found at levels over 2 μg g^{-1} (wet weight, or 10 μg g^{-1} dry weight), the limit set by such international guidelines as the Hong Kong Food and Environmental Hygiene Department (Copes *et al.* 2008). Cadmium in the environment is strongly linked to natural physical processes, such as coastal upwelling, and the presence of certain rocks and sediments, including phosphorite, which is mined near Bahía de La Paz (Riley 1989). The circulation of currents in the eastern Pacific Ocean yields concentrations of 100 ng Cd L^{-1}, three-to-five times higher than the levels seen in the western Atlantic Ocean. In general, mollusks collected along most of the North Pacific Coast from Alaska southwards have almost twice the cadmium concentrations as those gathered from the Atlantic coast (Kruzynski 2003). In Baja California Sur, Martín and Broenkow (1975) were among the first to report cadmium levels as high as 20.9 μg g^{-1} in plankton. Cheng *et al.* (1976) found exceptionally high concentrations of 100 to 200 μg Cd g^{-1} (dry weight) in samples of the insect sea skater *Halobates* spp., collected off Baja California. Bahía Tortugas on the west coast, and Bahía de los Ángeles, on the east side of the Baja California Peninsula, are subject to coastal upwellings and it is there that some of the highest cadmium levels have been reported, including concentrations as high as 70.2 and 27 μg g^{-1}, respectively (Gutiérrez-Galindo *et al.* 1999). Along the northern shore of Bahía de La Paz, which has very little anthropogenic activity, Méndez *et al.* (2006) found up to 11.1 μg Cd g^{-1} in the clam *M. squalida*. In kidney samples from two species of turtles, *Chelonia mydas* and *Lepidochelis olivacea*, killed incidentally during fishing activities in Bahía Magdalena, cadmium concentrations reached 653 μg g^{-1} and 274 μg g^{-1}, respectively; the highest concentrations reported in marine turtles (Gardner *et al.* 2004). Elevated levels have also been found in stranded whales in this area, with concentrations equal to, or above, 400 μg Cd g^{-1}, indicative of renal dysfunction (Puls 1988).

High cadmium levels have also been reported in coastal areas on the east side of the Gulf of California, due to the influence of agricultural activities. At Laguna de Navachiste in Sonora, Páez-Osuna *et al.* (1991) sampled the Cortez oyster, *Crassostrea corteziensis*, and found high levels of cadmium, up to 18.2 μg g^{-1}.

4.3. Arsenic and mercury

About one-third of the arsenic in the Earth's atmosphere is of natural origin; mostly from volcanic eruptions. Mining, smelting and fossil fuel combustion are the main industrial processes that contribute to arsenic contamination in air, water and soil. While Mexican legislation does not address this toxin, the FDA (2003) places limits of 76 μg As g^{-1} for crustaceans and 86 μg As g^{-1} for mollusks. Compared to cadmium, arsenic is less frequently sampled in marine animals. No currently available reports have detected levels above the maximum allowable FDA limits in marine animals from northwestern Mexico.

Mercury is a highly toxic element that occurs naturally in volcanic eruptions and rock deposits, but that also appears as an anthropogenic contaminant from chemical plants and coal-fired power plants. The FDA (2003) establishes a maximum allowable limit of 1.0 μg Hg g^{-1} (wet weight) for seafood. Gutiérrez-Galindo and Flores-Muñoz (1986) mention that 11–17 metric tons are added to the Pacific Basin each year between Punta Concepción, on the east side of the Baja California Peninsula, and Punta Colonet, on the west side near Ensenada. A study of mercury emissions in Southern California concluded that 74% of emissions enter the sea via the atmosphere, while the remaining 26% arrives in waste waters from metropolitan centers in that area (Eganhouse *et al.* 1976, Stephenson *et al.* 1979). Mercury levels in marine organisms from northwestern Mexico are below the level established by the FDA for human consumption.

5. DISCUSSION AND CONCLUSIONS

The extensive bibliographic review carried out during the elaboration of this chapter shows that from a historical perspective pesticide levels in the Gulf of California are low compared to those in other regions, such as the coastal US, the Mediterranean Sea, and the Gulf of Mexico (Carvalho *et al.* 2002, Niño-Torres *et al.* 2009). Differences between the Gulf of California and other regions have been compared to concentrations of HCHs, CHOLRs, and DDTs in turtles, blue whales, sea lions and porpoises (*vaquitas*) (Niño-Torres *et al.* 2009, 2010), and in sediments from many localities along the eastern coast of the Gulf of California (Sericano *et al.* 1990, Carvalho *et al.* 2002).

Of the 17 persistent organic compounds covered by the Stockholm Convention, 9 are OC (DDT, aldrin, endrin, mirex, toxaphene, hexachlorobenzene, chlordane and heptachlor, lindane and Clordecone). As a signatory to the Convention, Mexico is committed to controlling the use of these compounds, but it is clear that some of them are still being utilized. The most frequently detected substance—and the one most often found in high concentrations—is lindane, which is known to have serious effects on human health and on a wide range of animals in natural populations because of its bio-magnification properties in the trophic chain. Significant alterations caused by OC have been documented at both the physiological and molecular levels. Kalantzi *et al.* (2004), for example, noted that tumor cells in breast tissue contain lindane, which induces genotoxic effects. Thus, both human and environmental health is at a high risk from this pesticide. Relatively low concentrations of DDT are found in sediments and in numerous organisms; however, high percentages (up to 100% in some studies) in test samples containing DDE, a rapidly degradable metabolite of DDT, suggest that DDT is currently being used, though at lower levels than in the 1970s–1990s, when DDT was banned in many countries. As elsewhere, DDT residues will continue to cycle for years in aquatic systems until the degradation process is completed.

Despite their implementation several decades ago in other countries, there is little information from systematic monitoring programs of pollution in northwestern Mexico. Instead, most of the data available come from localized studies characterized by high seasonal and spatial variation in different matrixes (water, sediments, biota), which makes it impossible to compare the results obtained, or determine tendencies and their evolution over time, and then relate them to existing sources of pollutants. Moreover, several studies focused on migratory organisms such as birds, marine mammals and reptiles that are not representative of the environment where the data was collected, with the result that the contaminants detected in those organisms may well have originated in other regions.

The presence of pesticides in filtering (mollusks) and benthic (shrimp and fish) organisms, as well as in water and sediments from the eastern coast of the Gulf of California reflect the problematic in this region due to its characteristic intensive agricultural activity. Higher pesticide concentrations occur in the summer months as a result of the high agricultural production and heavy rainfall that release pesticides held in the soil through runoff and agricultural field drains and eventually deposit them as pollutants in coastal waters. Other processes involved are the displacement of sediments, evaporation, and transport by wind in the form of spray. Also, some chemical substances are subject to chemical and biological transformations that may play an important role in pesticide stability (decay rate) and distribution in coastal ecosystems.

The sensitivity of the pesticide detection and extraction methods used with water, sediments, living matter, food, and other matter are keys to the reliability of any environmental diagnosis. But it is important to note that pollutants may be present in the environment in trace amounts that cannot be detected and, therefore, are not subject to analysis. Every year, new pesticides appear on the market to treat a multitude of insect and other infestations. Their effect on human health is unknown though they may accumulate through the ingestion of contaminated drinking water, milk, plants, seafood, and other products (Abou-Arab 1999, Galindo *et al.* 1999b, Burgos-Hernández *et al.* 2005, Nag and Raikwar 2008, Díaz *et al.* 2009).

With respect to cadmium and lead, several areas of northwestern Mexico have registered high levels in plants and animals. In the case of the former, studies have shown that it is of geological origin. Lead pollution, in contrast, is frequently associated with the use of gasoline with a high content of this element, despite the fact that leaded gasoline has not been used since the 1990s. However, high lead concentrations could also be due to the presence of minerals such as galena. High concentrations of arsenic and mercury have not yet been reported in plants and animals in northwestern Mexico.

6. RECOMMENDATIONS

Given the complexity of these chemical compounds, evaluating pollutants in the marine environment is extremely difficult, and is made even more complicated by such factors as diversity, seasonality and geographical location. Using biomarkers that make it possible to measure exposures and the adverse effects of pesticides at different levels of biological organization may provide an effective way of evaluating the severity of these pollutants and the mechanisms of the toxic actions they produce. Bivalves have demonstrated their value as sentinel species in numerous studies and systematic monitoring and surveillance programs in many countries (France, the US, the UK, Scandinavia, and others). In Mexico, however, systematic monitoring programs do not exist except for a few specific, isolated studies, insufficient to conduct evaluations of the behavior and transformation of pollutants. Designing and implementing programs of this kind would lead to collecting the data that the authorities require to adequately regulate the sale and use of persistent toxic compounds.

International standardization of analytic methodologies is another necessity. In addition, all new compounds must be adequately evaluated. The effective identification of potentially toxic substances will make it possible to detect them and, perhaps, to determine how they affect different organisms.

Specific regulations for, and training in, the handling and use of pesticides, accompanied by strict monitoring, should be implemented in this region to prevent the utilization of banned pesticides and the misuse of authorized substances. Also, it is imperative that the potential impact of these compounds on fisheries and human health be communicated to all users and inhabitants of the region.

Finally, the data provided in this study suggest the importance of homogenizing international criteria to better define laws and regulations regarding the allowable limits for heavy metal content in plants and animals destined for human consumption.

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CATTLE IMPACT ON SOIL AND VEGETATION OF THE SEASONALLY DRY TROPICAL FOREST OF BAJA CALIFORNIA SUR

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An assessment of livestock grazing pressure on the seasonally dry tropical forest (SDTF) of the lowlands of the Sierra La Laguna Biosphere Reserve is shown in this study. It was done through an experiment that excluded cattle from a study plot for 10 years. The treatments were with total exclusion and without exclusion. Each treatment included an area of 2,500 m^2 and had one repetition. Community resilience to the effect of continuous cattle grazing on the physical and chemical characteristics of soil, structural features of vegetation, and diversity were measured. Higher clay contents were obtained in the soils of the ungrazed areas. In the grazed areas, higher soil surface temperatures, higher contents of sand, nitrate, iron, and lower pHs were recorded. These results indicated differences in moisture availability and changes in biogeochemical cycles. Vegetation response in ungrazed areas showed this plant community is resilient to short periods of cattle exclusion because we obtained changes in species composition, species turnover, higher species richness and diversity, and increases in height, stem density, and crown cover of trees, shrubs, vines, and herbs. Our results showed that, even though grazing activities have occurred for centuries in the region, the SDTF had a positive response to cattle exclusion in a short recovery time. We believe that adequate management strategies could be implemented to allow natural regeneration in several areas of the SDTF of this Biosphere Reserve.

Keywords: diversity, livestock exclusion, Mexico, Sierra La Laguna Biosphere Reserve, soil recovery, structural change, tropical deciduous forest, vegetation.

1. INTRODUCTION

The seasonally dry tropical forest (SDTF) is one of the vegetation types with the greatest area in tropical and subtropical regions, covering 42% of the tropical vegetation worldwide (Murphy and Lugo 1995). It is also one of the most threatened ecosystems due to the conversion of these areas to agriculture, increasing human population density, habitat fragmentation, fire, and more recently because of climate change (Gillespie *et al.* 2000, Miles *et al.* 2006). Wood extraction for fuel and the allowed overgrazing by livestock are the most common human activities that lower biodiversity in these tropical forest communities (FAO 1986, Murphy and Lugo 1986, Janzen 1988, Stern *et al.* 2002).

In Mexico, this ecosystem covers about 10% of the country (Rzedowski 1978), but less than 27% remains undamaged, which is about 4% of the total area of the country (Trejo and Dirzo 2000). Most of the SDTFs in Mexico follow the same pattern of resource exploitation. A continuous land conversion to agriculture and induced grasslands is recorded in most of the areas covered by the SDTFs (Arriaga and Cancino 1992, Burgos and Maass 2004, Castillo *et al.* 2005, Álvarez-Yépiz *et al.* 2008, Galicia *et al.* 2008). Livestock activities prevail and local ranchers breed cattle or goats as their main commercial activity.

In the Baja California Peninsula this ecosystem grows in the southern portion (Cape Region) where it reaches its northernmost limit. This SDTF is isolated from the continent by the Gulf of California, and its contact with the northern zones of greater aridity has resulted in a high level of endemism (Lott and Atkinson 2006). In the Cape Region, resource exploitation has historically followed an extensive and extractive pattern of wildlife harvesting. The extensive use of plant resources dates from the colonial period, when activities such as agriculture, cattle raising, and wood extraction started as peripheral activities associated with mining (Amao 1997). This pattern of land use gave rise to most of the human settlements established in the Sierra La Laguna and its surrounding foothills. The SDTF currently supports a variety of human activities such as livestock production, wood gathering for fuel, tree harvesting for local use, local agriculture and hunting of native wildlife (Arriaga and Breceda 1999).

The forest communities of the low- and middle-lands of the Cape Region have been exposed to a continuous and increasing grazing pressure since the Jesuits arrived to the Peninsula more than three centuries ago (Arriaga and Cancino 1992). These areas have remained since then as the largest livestock-husbandry regions of Baja California Sur. The type of stock farming by local inhabitants is extensive, sedentary, and its production is almost all for self-sustenance. Most of the ranches occurring in the tropical dry forest raise cattle at mean densities of 0.133 individuals per hectare with little breeding management because they raise mixed-breed cattle (Arriaga and Cancino 1992). Bovines forage in pastures and on leaves, stems, and fruits of numerous herbs, shrubs, and trees. Only during the dry season do some ranchers keep livestock in stables and feed them with alfalfa, sorghum, corn, hay, or food supplements. Most of the cattle are either sold alive or are slaughtered for consumption at the ranches. Other types of livestock like goats are also raised in the area, but at lower mean densities (0.036 individuals per hectare). Pigs and poultry are also produced, but mostly for the ranchers´ own consumption (Arriaga and Cancino 1992).

The range capacity of the SDTF has been estimated to be 30 hectares per animal per year by the national rangeland office (Martínez-Balboa 1981). Arriaga and Cancino (1992) estimated a carrying capacity for the low- and middle-lands of the Sierra La Laguna Biosphere Reserve as 9.11 hectares per animal, a value that implies overgrazing in the area. This ecosystem is supporting cattle three times more than that recommended by the national rangeland office.

Overgrazing of numerous perennial forage species of the SDTF is evident by the damage on the crowns, stems, and bark of a large number of shrubs and trees. One hundred and thirteen plant species have been recorded as forage resources (Arriaga and Cancino 1992). The foraged species belong to 45 families, with Fabaceae, Poaceae, and Asteraceae as the families with the highest number of species. The Poaceae includes a large number of introduced species (Arriaga and Cancino 1992). Ranchers cultivated grasslands of the African buffel grass, *Cenchrus ciliaris* (L.) in experimental plots in the 1960s, but these were abandoned during severely dry years. However, some of these species remain in some of the abandoned plots or in the wilderness as weeds.

This chapter shows an assessment of livestock grazing pressure on the SDTF of the lowlands of the Sierra La Laguna Biosphere Reserve. It was done through an experiment that excluded cattle in a 2-ha study plot for 10 years and by addressing the following questions: How does cattle foraging influence microenvironmental conditions? To what extent are soil characteristics affected by continuous livestock grazing? How are structural features and diversity affected by grazing? Is the plant community resilient to short periods of cattle exclusion?

2. MATERIALS AND METHODS

2.1. Study site

The study was made at the Sierra La Laguna Biosphere Reserve in the southern portion of the Baja California Peninsula (23°21'-23°42' N; 109°46'-110°10' W). Here the SDTF grows from 300 to 800 m a.s.l. It covers about 170,500 ha and has the most diverse type of vegetation in the Peninsula (Arriaga and Ortega 1988). The total annual rainfall average in the area is 316 mm for a 42-y period, with a dry season from late October to July, and winter rains can occur. The mean monthly temperature is 23.6 °C (García 1981). Soils are Lithic Leptosols (formerly Lithosols) or Regosols with a sandy texture, and they are rocky, shallow, and have high organic-matter content (Maya 1991). Four hundred and fifty-seven species have been described in this plant community. The structurally important families are Fabaceae, Cactaceae, Euphorbiaceae, Asteraceae, and Acanthaceae (Arriaga and León 1989, León de la Luz and Domínguez 1989).

2.2. Sampling plots

Within the tropical dry forest, at 450-m a.s.l., a 2-ha study plot was laid out. The study plot was divided into 4 treatments to avoid grazing by bovine cattle. The treatments were 1) total exclusion, 2) exclusion during the rainy season, 3) exclusion during the dry season, and 4) without exclusion. Each treatment included an area of 2,500 m^2 and had one repetition. In this chapter we will only present the results for the total exclusion (TE) and without exclusion (WE) treatments. All perennial plants were identified *in situ* and by consulting the CIBNOR HCIB herbarium. The nomenclature follows Wiggins (1980) mostly, but updates were made with the advice of several taxonomists and by consulting online databases (Tropicos.org 2009). Perennial plants were mapped and recorded within the study site, and their height and crown cover were measured at the beginning and at the end (10-years later) of the study. Crown cover was measured as an estimate of dominance and calculated using the ellipse function: $C = \pi \cdot 0.25 \cdot D_1 \cdot D_2$; where D_1, is the largest crown diameter and D_2, the diameter perpendicular to D_1. Stem density and species richness were recorded for each condition, and species diversity and evenness were estimated using the Shannon function (Magurran 1988). Diversity indices were compared using *t*-tests (Zar 1974).

2.3. Physical environment and soil characteristics

Changes in soil surface temperatures beneath the canopy of plant clusters and in open spaces were compared in the study plot. We randomly chose plant clusters bearing the physiognomic-dominant perennial species *Lysiloma divaricatum* and *Stenocereus thurberi* as one group or *Tecoma stans* and *Jatropha vernicosa* as another group, under which to measure soil surface temperatures. Five replicates for either of these associations were measured in the WE and TE treatments. Soil surface temperatures were recorded during 11-h each day for three days at the end of the study.

Physical and chemical soil characteristics were also compared in the study plot at the end of the study. Each exclusion treatment was divided into ten quadrants

(20 × 25 m). In each quadrant two soil samples were taken (depths 0 to 5 cm and 5 to 15 cm). These samples were air-dried and the following physical and chemical analyses were obtained: texture (sieve and pipette, Folk 1980), pH and electric conductivity (potentiometer and conductivity bridge, Jackson 1982), organic matter content (Walkley-Black 1934), calcium, magnesium, sodium, potassium, iron (by atomic absorption spectrophotometry), carbonates and bicarbonates (Reitemeier 1946), nitrites and nitrates (Strickland and Parsons 1972), and total and assimilable nitrogen (Dahnke and Johnson 1990). Differences in soil surface temperatures and physical and chemical soil variables were tested by means of Student´s t-test using the Statistica software (StatSoft Inc. 2009).

3. RESULTS

3.1. Physical environment and soil characteristics

Soil temperature records beneath the canopy of the clusters and in open spaces for the physiognomic-dominant associations are shown in Figure 1. There were significant differences between soil temperatures as recorded beneath the canopy versus those recorded in open spaces in the WE treatment (t = 2.229; *d.f.* = 108; p = 0.028). A difference of almost 12.5 °C was obtained for the warmest hours of the day between shade and unshaded conditions in the WE treatment (see Figure 1a). In the TE treatment, although temperatures were higher in open spaces, no significant differences were recorded between the shade provided by the canopy and the open spaces (t = 1.705; *d.f.* = 108; p = 0.091; see Figure 1b). In this area there was a greater recovery of crown cover that decreased soil surface temperatures in open spaces.

The results for soil variables were compared for the WE and TE treatments and are shown in Table 1. In the TE treatment significantly higher clay contents were obtained in both layers, 0-5 cm (t = 2.402; *d.f.* = 18; p = 0.027) and 5-15 cm (t = 2.248; *d.f.* = 18; p = 0.037). Many other differences were found in the WE treatment but only in the 5-to 15-cm layer (see Table 1), which were higher contents of sand (t = 2.113; *d.f.* = 18; p = 0.048), nitrate (t = 2.573; *d.f.* = 18; p = 0.019), and iron (t = 3.787; *d.f.* = 18; p = 0.001), and lower values in pH (t = 2.507; *d.f.* = 18; p = 0.021). These differences are relevant because they indicate differences in moisture availability and changes in biogeochemical cycles.

3.2. Vegetation structure and diversity

Contrasting changes in structural characteristics and diversity were recorded after 10 years in the WE and TE treatments (see Table 2). Species richness, diversity, and evenness remained almost unchanged in the WE treatment. No significant differences were obtained in diversity indices in this treatment when initial conditions

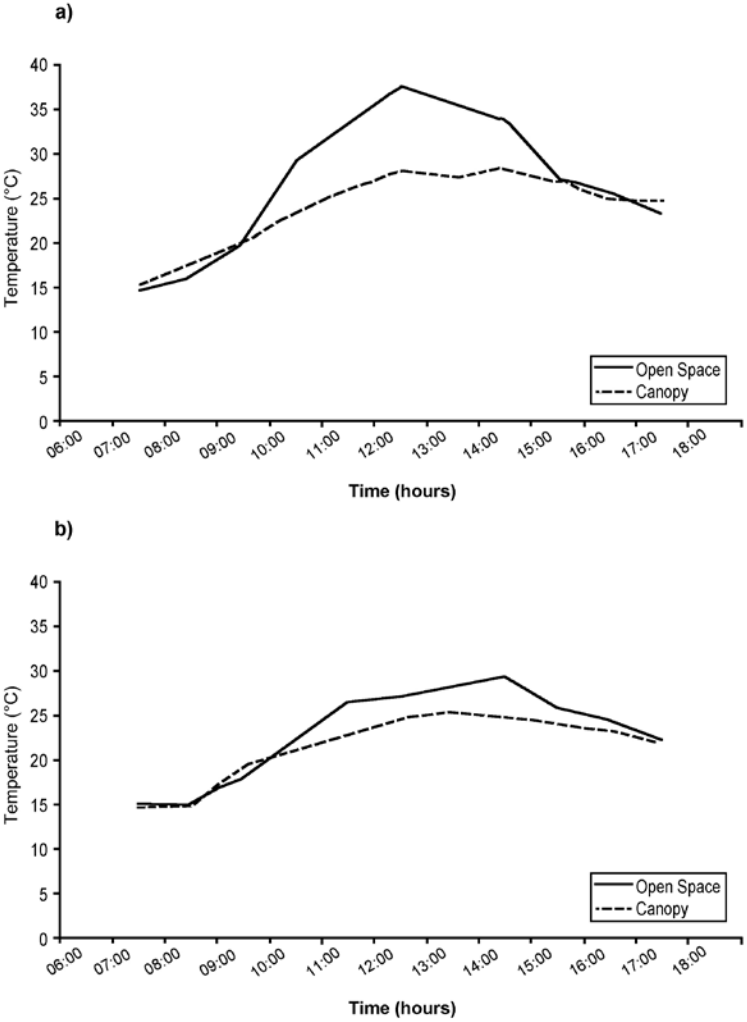

FIGURE 1. Soil surface temperatures for open spaces and shades provided by tree canopy in the 2-ha study plot of the STDF of Baja California Sur. a) without exclusion of foraging cattle; b) total exclusion treatment of foraging cattle.

were compared with those obtained 10 years later ($t = 0.045$; *d.f.* = 2338.4; $p = 0.964$). The recruitment of individuals was high in the WE treatment during the study period because stem density doubled, though crown cover decreased slightly from the initial conditions (-2.4%). The opposite was obtained in the TE treatment where species richness, diversity, evenness, stem density, and crown cover increased after

TABLE 1. Student's *t*—test comparisons of the physical and chemical data of the soil in the study plots. *n* = 10; *d.f.* =18. Significance level: *$p \le 0.05$; **$p \le 0.001$; *s.d.* = standard deviation.

	Total exclusion		Without exclusion			
Variables	Average	*s.d.*	Average	*s.d.*	*t*	*p*
0- to 5- cm depth						
Organic matter (%)	3.08	2.38	2.25	1.07	0.996	0.332
pH	6.77	0.3	6.81	0.34	-0.028	0.781
Electric conductivity (S m–1)	0.0235	98.08	0.0216	59.02	0.53	0.602
Calcium (meq 100 g soil $^{-1}$)	396.387	203.37	338.056	114.24	0.79	0.439
Magnesium (meq 100 g soil $^{-1}$)	90.713	38.35	86.934	35.23	0.229	0.821
Sodium (meq 100 g soil $^{-1}$)	0.345	0.19	0.269	0.29	0.68	0.504
Potassium (meq 100 g soil $^{-1}$)	0.072	0.04	0.122	0.15	-0.984	0.337
Iron (meq 100 g soil $^{-1}$)	77.46	52.15	60.239	46.66	0.778	0.446
Bicarbonates (meq 100 g soil $^{-1}$)	476.727	226.85	453.773	137.17	0.273	0.787
Nitrates (meq 100 g soil $^{-1}$)	0.497	0.11	0.574	0.18	-1.139	0.269
Sand (%)	83.05	5.68	86.67	2.59	-1.831	0.083
Silt (%)	8.94	3.91	7.19	2.14	0.47	0.643
Clay (%)	8	2.3	6.13	0.88	**2.402**	**0.027**
Total nitrogen (%)	0.141	0.13	0.11	0.05	0.648	0.524
Assimilable nitrogen (%)	0.002	0	0.001	0	0.935	0.362
5- to 15- cm depth						
Organic matter (%)	0.98	0.74	1.07	0.72	1.108	0.282
pH	6.84	0.28	6.58	0.16	**2.507**	**0.021***
Electric conductivity (S m^{-1})	0.0094	21.15	0.0109	60.53	-0.764	0.454
Calcium (meq 100 g soil $^{-1}$)	136.672	28.26	153.788	74.27	-0.681	0.504
Magnesium (meq 100 g soil $^{-1}$)	39.41	11.86	48.57	31.86	-0.852	0.405
Sodium (meq 100 g soil^{-1})	0.523	0.38	0.25	0.19	2.01	0.058
Potassium (meq 100 g soil $^{-1}$)	0.033	0.02	0.072	0.05	-1.948	0.067
Iron (meq 100 g soil $^{-1}$)	152.672	56	61.112	52.03	**3.787**	**0.001****
Bicarbonates (meq 100 g soil $^{-1}$)	159.581	37.15	204.052	105.25	-1.259	0.223
Nitrates (meq 100 g soil $^{-1}$)	0.416	0.115	0.561	0.136	**-2.573**	**0.019***
Sand (%)	78.24	10.31	85.41	2.93	**-2.113**	**0.048***
Silt (%)	10.66	4.72	8.01	2.51	0.636	0.532
Clay (%)	11.08	6.3	6.57	0.74	**2.248**	**0.037***
Total nitrogen (%)	0.166	0.37	0.05	0.03	0.966	0.346
Assimilable nitrogen (%)	0.0005	0	0.0005	0	-0.019	0.984

TABLE 2. Community characteristics of the study plot and cattle-exclusion experiment in the STDF of the Sierra La Laguna in Baja California Sur. Abbreviations: WE = without exclusion of grazing cattle; TE = total exclusion of grazing cattle.

Exclusion Treatment	Species Richness (S)	Diversity Index (H')	Evenness (J)	Density (ind·ha^{-1})	Crown Cover (%)
WE initial	39	2.67	0.73	1.05	85.79
WE 10-y later	37	2.63	0.73	2.04	83.41
TE initial	29	2.32	0.69	1.26	73.81
TE 10-y later	43	2.81	0.75	1.43	93.31

cattle exclusion for 10 years (see Table 2). Diversity indices were significantly different when initial and final conditions were compared. Diversity was higher in the excluded plot ($t = 12.327$; $d.f. = 2685.7$; $p = 0.000$). There was a clear increase in crown cover in the TE treatment (19.5%).

Changes in structural characteristics for both treatments are shown for twenty-dominant perennial-plant species in Figures 2 and 3. Species response and recovery were contrasting in both treatments. In the WE treatment there was an important recovery in stem density of species like *Tecoma stans*, *Mimosa xanti*, *Stenocereus thurberi*, *Lysiloma divaricatum*, *Coursetia glandulosa*, *Viguiera* sp., *Senna villosa*, *Bursera microphylla*, and *Euphorbia lagunensis* (see Figure 2a). Species that increased in stem density did not necessarily increase their crown cover compared to initial conditions. *Lysiloma divaricatum* had the greatest loss in crown cover in the grazed area. This species decreased 2.4 times in crown cover compared to initial conditions (see Figure 2b). This result was surely caused by cattle grazing pressure because this species is the most palatable of the legumes growing in the study plot. The spiny legumes *Mimosa xanti* and *Haematoxylum brasiletto* increased their crown cover as did *Bursera microphylla*, a species with an aromatic sap not palatable to cattle (see Figure 2b).

In the TE treatment the species with the greatest recruitment in stem density were *Lysiloma divaricatum*, *Stenocereus thurberi*, *Mimosa xanti*, *Senna villosa*, and *Bursera microphylla* (see Figure 3a). We also recorded 21 species that were not recorded during initial conditions (see Table 2). In this treatment legumes like *L. divaricatum*, *Haematoxylum brasiletto*, *Chloroleucon mangense*, *Mimosa xanti*, *S. villosa*, *Erythrina*

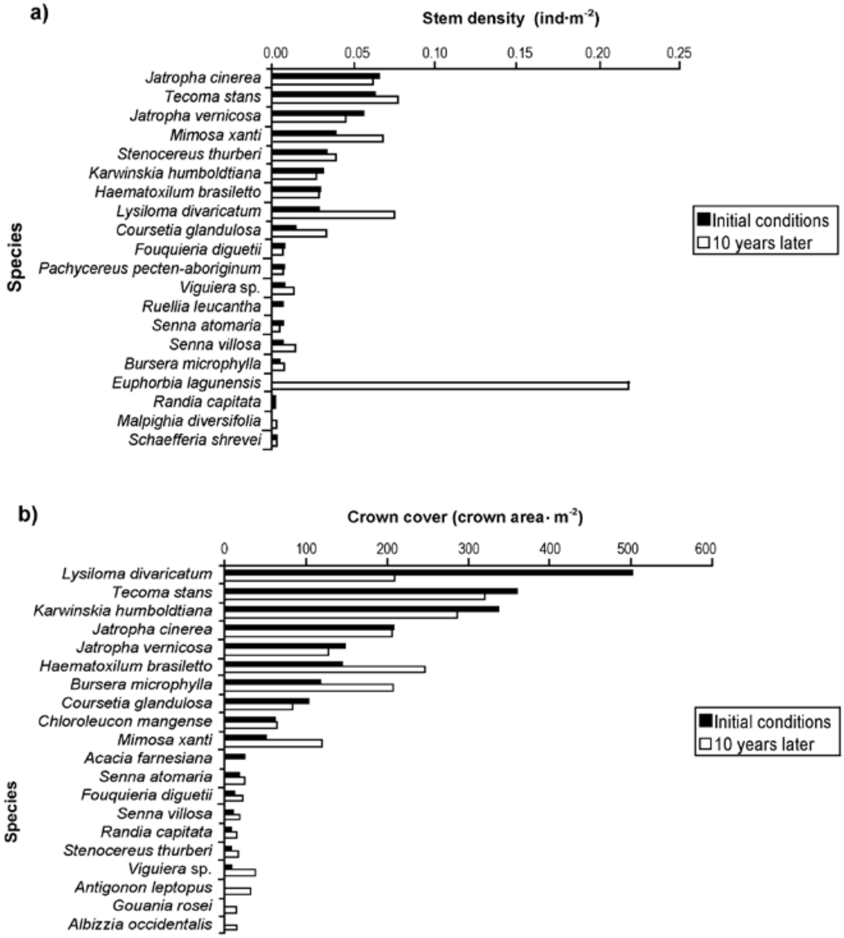

FIGURE 2. Changes in structural characteristics for 20 dominant perennial plant species in the Without Exclusion (WE) treatment of the STDF of the Sierra La Laguna Biosphere Reserve. a) stem density, and b) crown cover.

flabelliformis, and *Albizzia occidentalis* had the highest recovery in crown cover (see Figure 3b). Particularly *L. divaricatum* had the most striking differences, by increasing 1.3 times in stem density and 2.1 times in crown cover compared to initial conditions in the ungrazed area. On the contrary, unpalatable species like *Tecoma stans*, *Jatropha cinerea*, and *Karwinskia humboldtiana*, that have also been described as characteristic of disturbed habitats, reduced their crown cover by the end of the study (see Figure 3b).

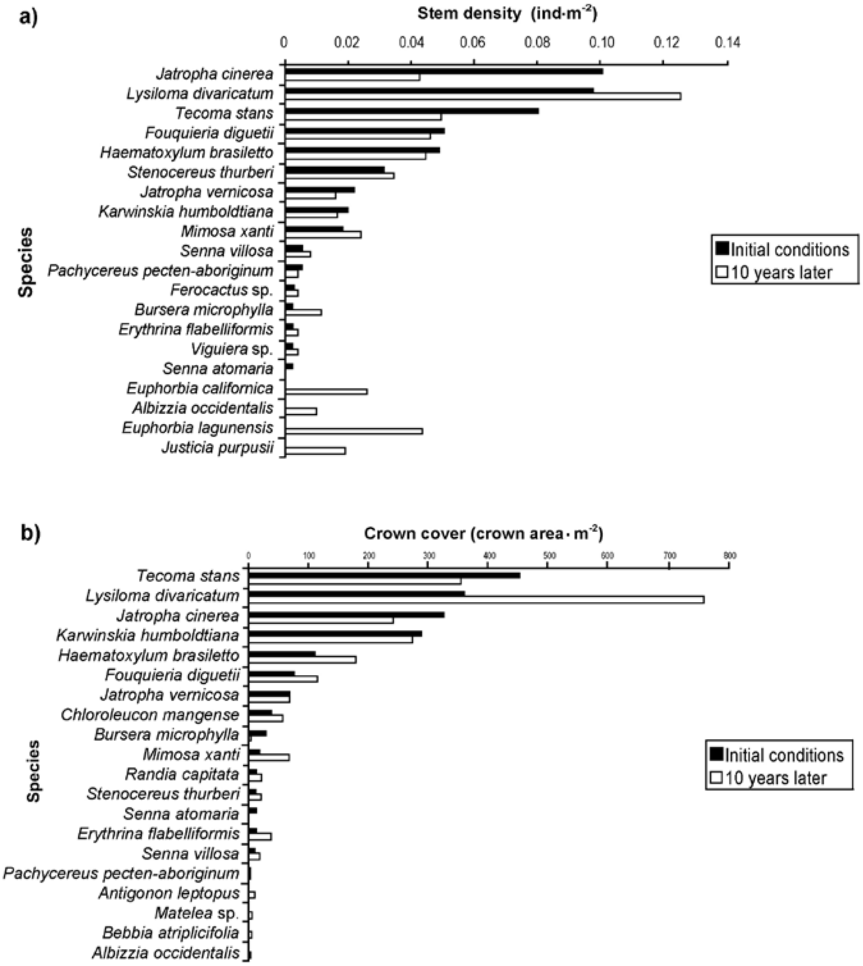

FIGURE 3. Changes in structural characteristics for 20 dominant perennial plant species in the Total Exclusion (TE) treatment of the STDF of the Sierra La Laguna Biosphere Reserve. a) stem density, and b) crown cover.

4. DISCUSSION

4.1. Physical environment and soil characteristics

After 10 years of cattle exclusion, our study showed that grazing changed the physical environment and soil characteristics of the SDTF. Significant differences in soil surface temperatures between shade and unshaded areas in the WE treatment were obtained (see Figure 1a). The differences in soil surface temperatures in this study plot (12.5 °C less at the warmest hours of the day) can be explained as the result of a decrease in crown cover (2.4%; see Table 2). In the ungrazed plot (TE), crown recovery provided more shade, decreasing soil surface temperatures and leaving less unshaded areas (see Figure 1b). An increase of 19.5% in crown cover was obtained in this treatment (see Table 2). These results indicate that protection against radiation by the dominant plants appears to be an important factor in the pattern of species establishment. Several studies have documented that safe sites are needed for seed germination and seedling establishment, and their occurrence is associated with cattle exclusion and soil conditions in the SDTF (Arriaga *et al.* 1993; Dalling and Hubbell 2002, Griscom *et al.* 2007).

Based on the results obtained for structure and diversity between the TE and WE treatments, we expected a significantly lower quantity of organic matter in the soil of the WE treatment. However, organic-matter content was not significantly different from that obtained in the TE treatment (see Table 1), which suggests that dung is quickly integrated into soil rapidly enough to nearly match the level of the TE treatment. As mentioned earlier, most of the livestock diet is composed of tree species (Arriaga and Cancino 1992), whose biomass would take longer to incorporate into soil organic matter in the TE treatment.

The significantly higher nitrate content obtained in the WE treatment (see Table 1) indicates that cattle provide feces and urine that can be converted to nitrates by soil microorganisms. In the TE treatment, where a normal nitrogen cycle was occurring, many stages of vegetative decomposition were required before nitrogen was liberated from organic litter on the soil. Additionally, higher nitrification rates produce lower pH values, which explained the significantly lower pH in the WE treatment (see Table 1). The greater biomass in the TE treatment suggests a greater consumption of nitric forms of nitrogen by plants, which contributes to increases in pH (Duchaufour 1995).

Iron content was significantly higher in the TE treatment (see Table 1). A higher pH can explain this result because iron solubility decreases inversely to pH, reducing its lixiviation and use by plants (Duchaufour 1995). Some studies indicate that land subjected to long periods of intensive cattle grazing show declines in total nitrogen, cation-exchange capacity, and interchangeable calcium and magnesium (Turner 1998, Ayuba 2001). Higher values of these variables were found in the TE treatment (see Table 1), which suggests this phenomenon has taken place in the grazed areas.

The herbaceous layer increases soil infiltration rates and shades the soil, leading to lower soil surface temperatures and evaporation rates (see Figure 1 and Table 1). It is indirectly confirmed by the higher clay content in both sampled layers (0–5 and 5–15 cm) of the TE treatment (see Table 1) because clay formation requires humid conditions, which are not present in the WE treatment where the cattle have removed the herbaceous layer. Moreover, the results suggest that eluviated clay particles from the soil surface were added to the clay that was already in the subsurface. Clay promotes particle aggregation, improves soil stability, and increases moisture-retention and cationic-interchange capacity; all of these would contribute to decrease soil degradation in the TE treatment. Conversely, in the WE treatment, cattle grazing would cause mechanical soil degradation processes, such as compaction and destruction of soil aggregates (Parizek *et al.* 2002). Our results also support the argument that cattle grazing removed protective cover, increasing the surface area of bare soil that is then exposed to direct radiation, which triggers the mineralization of humic compounds (Salmon *et al.* 2008), increasing degradation. Based on all the previous information, we confirm that continuous livestock grazing affects soil characteristics and that overgrazing is a threat to the stability of the ecosystem.

4.2. Vegetation structure and diversity

The floristic composition of the SDTF also changed after 10 years of cattle exclusion, and the structural complexity of vegetation decreased with grazing. The analyses of floristic composition and diversity demonstrated that significantly lower species diversity was obtained in the WE treatment (see Table 2) compared with the ungrazed area. The TE treatment had a higher species richness and diversity (see Table 2) and also contributed more to overall species diversity with 21 species unique to this habitat (5 were vines, 13 were shrubs, and 3 were trees). Our results agree with those obtained for other SDTFs of Mexico and Central America. Álvarez-Yépiz *et al.* (2008) found that species density was lower in secondary forests (20 to 30 years of recovery) when these were compared with old-growth, tropical dry forests in Sonora, Mexico. Stern *et al.* (2002) found that intermittent grazing had a negative impact on the structure and diversity of the SDTF compared to an ungrazed area in northwestern Costa Rica.

Species that were abundant in both treatments included *Jatropha cinerea* and *Tecoma stans* (see Figures 2a and 3a). Some authors have reported that the main physiognomic trait of this SDTF is the abundance of *T. stans*, whose occurrence indicates a high disturbance of the overall ecosystem (González-Medrano, pers. comm.). The most abundant species in the WE treatment was *Euphorbia lagunensis* (see Figure 2a). This species was not recorded during initial conditions but had the highest recruitment in the grazed area. Its occurrence was not expected because it has been recorded at higher elevations of the Sierra La Laguna and as part of the seed bank of the oak-pine forest (Huft 1984, Arriaga and Mercado 2004). In contrast, several species in the TE treatment included species that are characteristic of more mature conditions, such as *Albizzia occidentalis* and *Erythrina flabelliformis* (see Figure 3a) although these were found at low densities. The lack of regeneration of *Senna atomaria* was evident in both areas. This is a dominant canopy species of the SDTF, but it had been completely extracted by local inhabitants in the study plots. The distinctive canopy species *Lysiloma divaricatum* had the highest response to the exclusion of cattle. It increased significantly in stem density and in crown cover in the ungrazed area (see Figures 3a and 3b). This species is the most affected by cattle grazing; it is a palatable legume that changed its small, pruned appearance to vigorous branched trees after 10 years of cattle exclusion. The average height in the grazed plot for this species was 0.56 ± 1.2 m, whereas in the ungrazed plot the average was 2.0 ± 1.3 m. The maximum height recorded for this species in the grazed plot was 7.5 m, whereas it was 12.2 m in the ungrazed plot.

Plant structure analyses (see Figures 2 and 3) between grazed and ungrazed areas emphasized the impact that cattle have on the SDTF structure. The vegetation response indicated this plant community is resilient to short periods of cattle exclusion and that a 10-year period is enough time to see changes in species composition, diversity recovery, species turnover, and increases in height, stem density, and crown cover of trees, shrubs, vines, and herbs. Griscom *et al.* (2007) obtained similar results in a forest regeneration plot in the dry tropical forest of Panama. They found that basal area, stem density, and species richness of trees, shrubs, vines, and herbs were significantly and positively affected by cattle exclusion. Rapid increases in height and crown cover have also been reported by some authors in neotropical secondary forests (Guariguata and Ostertag 2001). Other authors have found that certain features (canopy height, plant density, crown cover) recovered rapidly (in less than 20 years), whereas other features (including basal area and species richness) had not recovered after 40 years in the SDTF of Oaxaca, Mexico (Lebrija-Trejos *et al.* 2008). Vegetation response depends on the intensity of disturbance that a specific area has had and its previous changes in land use. Our results showed that, even though grazing activities have occurred for centuries in the region, the SDTF had a positive response to cattle exclusion in a short time. These results suggest rapid vegetation responses could be obtained if adequate management strategies to exclude cattle were implemented to recover and restore some areas of the SDTF.

Current management practices in the Sierra La Laguna Biosphere Reserve do not allow the regeneration of the tree species in grazed pastures by excluding cattle grazing. Some federal programs have been implemented by the National Commission on Natural Protected Areas to restore degraded areas of the SDTF within the reserve. However, these programs have been oriented to regenerate some locations with introduced species of *Agave*, or with shrub species that are already abundant, characteristic of disturbed habitats that arrest succession and that are not useful for local inhabitants (*i.e. Jatropha vernicosa, Tecoma stans*). On a smaller scale, some legumes (*i.e. Senna atomaria, Lysiloma divaricatum, Erythrina flabelliformis)* are being cultivated by local inhabitants on their own ranches. Seeds are germinated under shade, but there is a lack of assessment as to where to plant the legume saplings, without the monitoring of plant survival after planting. The regeneration of species that show limited regeneration, such as *Plumeria acutifolia, Bursera microphylla, Albizzia occidentalis* is not being enhanced at all. The great touristic development of the lowlands and coastal zone that surrounds this Biosphere Reserve has caused a massive removal of *B. microphylla*, and nothing is being done to limit these illegal activities, particularly outside of the Biosphere Reserve limits. We think several management strategies are necessary to allow the regeneration of the SDTF in this region. These should include temporary grazing cattle exclusion in different areas of the Biosphere Reserve. For the dominant species of the SDTF, the retention of adult trees, protection of saplings and seedlings from grazing, and the use of plant nurseries and larger plantings would be necessary to enhance further reforestation.

5. CONCLUSIONS

The SDTF has been exploited by man for more than three centuries, though exploitation of this ecosystem has not been planned or based on adequate management strategies. Our study shows that, even though grazing activities have occurred for centuries in the region, the SDTF will have a positive response to cattle exclusion in a short time.

Continuous livestock grazing deeply affects many soil characteristics, such as soil surface temperatures, infiltration, particle aggregation, and fertility. Even if the effect on soil is derived from direct modifications to the vegetation cover, it is cumulative and can overcome the resilient capacity of the soil.

Vegetation response has shown this plant community is resilient to short periods of cattle exclusion. The 10-year exclusion allowed us to see changes in species composition, diversity recovery, species turnover, and increases in height, stem density, and crown cover of trees, shrubs, vines, and herbs.

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IMPACT OF RANCHING ON WILDLIFE IN BAJA CALIFORNIA

Eric Mellink[1] and Joaquín Contreras[2]

Livestock have been present in Baja California since the 16th century when they were introduced by Spanish colonizers. However, for a long time animal husbandry remained in the form of small-scale operations. This changed in the 19th and 20th centuries when livestock numbers and areas used increased largely. In the process, burning, transhumance, harvesting of wild plants, and dry-time policies have been common practices. Despite the high numbers of cattle in Baja California, and its overall impacts on the habitat elsewhere, possible effects on Baja California rangelands have been neglected by agricultural officers and most academics, and the issue has been investigated only scantly. Overgrazing is probably widespread, but we think it is most severe, or noticeable, in the cool meadows of the northern mountains, where it has severely imperiled, or caused the extinction, of three endemic subspecies of California vole. Overgrazing is the likely cause of the disappearance of a number of meadows that were drained dry through gullies formed in particularly rainy years. Outside the grassy meadows, evidence for overgrazing is even scantier, although it has surely happened and might have impacted mule deer, pronghorn, bighorn sheep, mountain and California quails, California Bell's vireo and moles, among other species. Other likely, but poorly documented effects of animal ranching on wildlife include interference competition and the transmission of diseases and parasites from livestock to wildlife. Harvesting succulent plants to feed cattle can impair the habitat to support the native species. Grazing impacts upon wildlife habitat are probably aggravated by governmental programs that prevent cattle die-offs on the range during drought times by promoting high stocking rates, surely in excess of the range's carrying capacity at that time. In the whole, we believe livestock ranching has impacted wildlife throughout the Peninsula of Baja California, although the issue remains to be studied.

1. INTRODUCTION

In 1955, Rosarito de los Loya, a small community on the southern slope of the Sierra de San Pedro Mártir had 200 inhabitants who supported themselves with the cattle which they raised for meat, hides and cheese on the surrounding hills and, importantly, in an adjacent meadow. Things changed suddenly one morning in 1978 when, after heavy rains they woke to the unpleasant news that the meadow no longer existed: it had drained away through a gully created by the heavy runoff. Although this season was under the effect of El Niño, and rains were particularly heavy (see Figure 1), El Niño years are a common feature in northwestern Mexico, and this particular meadow had endured several such events before, although this was the rainiest year in half-a-century. Presumably, the meadow would not have disappeared if it had not been grazed so heavily as to impair the vegetation's capacity to protect the soil and retain water, and perhaps, if grazing of the upper reaches of the watershed had not lead to lower infiltration rates and higher runoff producing larger-than-normal river flow. In addition to its repercussion for the people that lived here, local populations of animals surely disappeared along with the meadow, including amphibians and, perhaps, California voles (*Microtus californicus*), whose three local subspecies are endangered (Mellink and Luévano 2005).

This is an example of how grazing by cattle can affect wildlife. However, grazing can be much more insidious, and in several places in the world its effects have been detected only after decades of research. No detailed long-term studies on rangeland conditions exist for Baja California, although one mid-term study has been carried out (Sosa-Ramírez and Franco Vizcaíno 2001), and the possibility of grazing impacts is neglected by many.

Throughout the world, grazing is the most subtle cause of habitat modification, yet the most widespread (Kelley 1990), and has damaged 80% of the streams and riparian ecosystems in arid regions of the western United States (U.S.D.I. in Belsky *et al.* 1999). Modifications result from changes in the competitive ability of plants as a result of their preferential use by grazing animals and/or the dissemination of their propagules, in what is known as "overgrazing" (Jordan 1993). This form of human dominance upon the environment is commonly unintentional, takes a long time to express itself, and is often inconspicuous, causing it to be overlooked in biological as well as administrative evaluations (Darling 1956). Despite ranching being the most widespread activity on the ranges of northwestern Mexico, and the known impacts on ranges elsewhere, its biological impacts along the Peninsula of Baja California have not been paid attention to. For example, the recent book "Del saqueo a la conservación: historia ambiental contemporánea de Baja California Sur, 1940–2003"

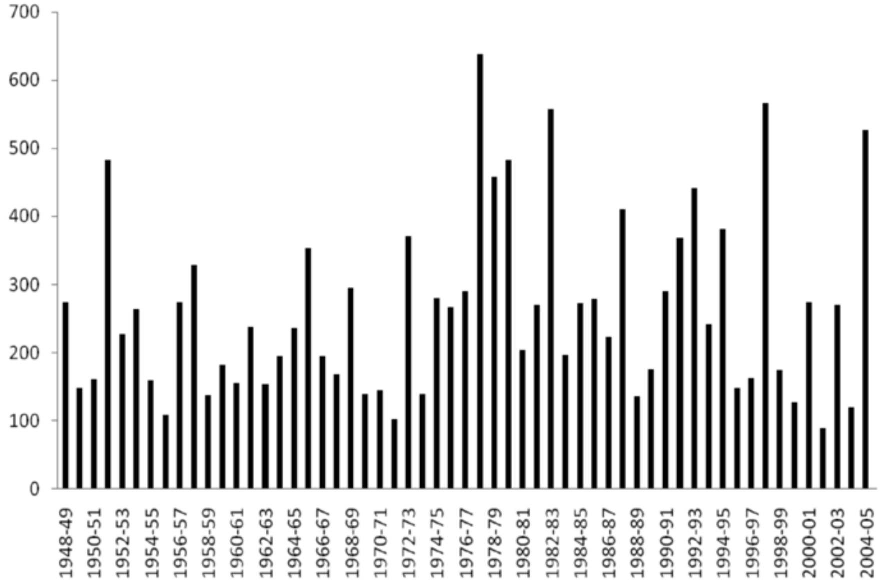

FIGURE 1. Rainfall in Ensenada, Baja California, during the rainy season (July of each year to June of the next). Data: Comisión Nacional del Agua.

("From plundering to conservation: contemporary environmental history of Baja California Sur, 1940–2003;" Cariño and Monteforte 2008) does not include a single paragraph to analyze the impact of animal husbandry on biota in it's over 700 pages of text. Likewise, in the corollary of a book on the oasis of the Peninsula (Rodríguez-Estrella and Arriaga 1997) there was no mention at all of ranching impacts on the biota. Federal agriculture officials concerned with rangelands for the state of Baja California have expressed to us their disbelief that rangelands are impacted by grazing; this feeling is, of course, reflected by the lack of governmental programs focused on range restoration.

This neglect can be due to the fact that degradation of semiarid ranges through grazing takes much longer than a human lifespan and, therefore, goes unnoticed, that it is less dramatic than, say, in grasslands, and the paucity of research on the matter. However, it is likely that ranching has impacted Baja California willdife (Mellink 1996), and, indeed, a meticulous research of the historical sources available lead to the conclusion that there had been a severe overgrazing in the Peninsula's northwestern ranges (Minnich and Franco-Vizcaíno 1998), particularly in and around the meadows of Sierra de San Pedro Mártir (Minnich *et al.* 1997), for

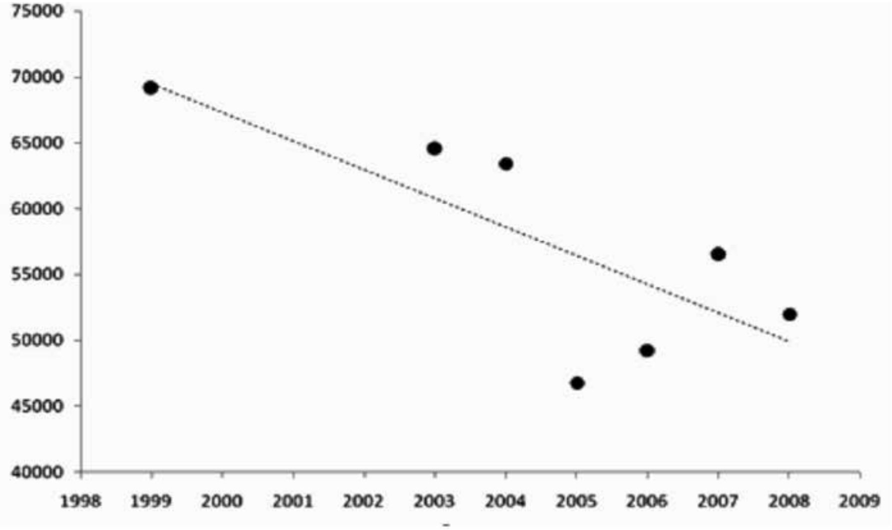

FIGURE 2. Number of heads of cattle in the Distrito de Desarrollo Rural 001, of the state of Baja California during the last 25 years. Data: DDR 001, Baja California, SAGARPA.

which Sosa-Ramírez and Franco-Vizcaíno (2001) recommended reducing grazing intensity in the Sierra's meadows "…to increase their grazing value and abundance of grasses and legumes."

The worst impacts upon native habitats come from the direct conversion of native vegetation to agriculture, but grazing can play a major role in habitat deterioration, as has been indicated for Sonora (Pérez-López 1992; López-Reyes 2006; Denogean *et al.* 2008), southwestern United States (Jordan 1993; Fleischner 1994; Noss 1994; Heffelfinger *et al.* 2006; Sommer *et al.* 2007), and the southern part of the Mexican Plateau (Mellink and Valenzuela 1992, 1995; Mellink 1994; Gonnet *et al.* 2001; Riojas-López and Mellink 2005), although some of the effects can be indirect and difficult to detect (Mellink 1989). Also, not always is grazing negative to the environment and, on the contrary, controlled grazing can be beneficial to it (Leopold 1933; Holechek 1981; Jordan 1993).

Although for the most part the overgrazing of rangelands of Baja California is neglected, the trend in number of cattle on the range suggests that such contempt is erroneous. Throughout the last 25 years the cattle herd of the Distrito de Desarrollo Rural 1 of the state of Baja California, which includes most of the state, has been diminishing despite the different governmental programs to stimulate ranching (see Figure 2). Such reduction reflects, we believe, a loss in the carrying capacity of the rangelands supporting this stock. The only other factor that could explain such reduction is a generalized reduction in the amount of rain. Although changes in amount of rain are often invoked as causative of biotic changes, in our case they can be discarded, given that, although they exhibit large inter-annual fluctuations, there is no long-term pattern (see Figure 1).

The objective of this chapter is to review, based on the limited information available as well as our own experience in the field, the apparent or likely impacts of grazing by livestock on wildlife in Baja California. We address mostly the northern part of the Peninsula, as we are more familiar with it. However, we include scant information from the southern half (the state of Baja California Sur) when appropriate. We do not include feral grazers on islands, as they have been reviewed elsewhere (Howell and Cade 1954; Mellink 2002; León de La Luz *et al.* 2003). Here, as "wildlife" we consider terrestrial and fresh water amphibians, reptiles, birds and mammals.

2. GEOGRAPHICAL SETTING

Baja California, the second longest peninsula in the world, is a narrow peninsula of over 1,200 km, and spanning over 10° of latitude. It has a rugged texture given by a long series of mountain ranges along it. Its abrupt topography, and the influence of two very different oceanic bodies (the Gulf of California to the east, and the Pacific Ocean to the west) creates a variety of climatic conditions, broadly ranging from subtropical in the south to extreme desert in the northeast, and Mediterranean in the northwest. A fundamental characteristic of the climate, especially in the northern half of the Peninsula, is the combination of series of drought years, alternating with some very wet ones, due to El Niño Southern Oscillation events. The southern part of the Peninsula very often experiences tropical cyclones, which only rarely reach into the northern Peninsula. Both dry and wet periods, and the occasional tropical cyclone have a strong impact on ranching, although knowledge of their effect is only anecdotal. A complete description of the Peninsula and its characteristics is beyond the scope of this chapter, but a insightfull account of it, along with a great map, is provided by Grismer (2002). A modern definition of its ecoregions can be found in González-Abraham *et al.* (2010).

The state of Baja California occupies the northern half of the Peninsula, and is typified by two major mountains: the Sierra de Juárez, in the north, and the Sierra de San Pedro Mártir, south of it. The second of these reaches above 3,000 m above sea level. On both sierras, but more at San Pedro Mártir, there are clear elevation vegetation patterns, from scrublands to conifer forests (Minnich *et al.* 1997). The northwestern Peninsula, under the effect of the California Current, has mediterranean habitats. In contrast, the center and northeast are covered by variants of the Sonoran Desert, caused by latitude and orographic shade.

3. HISTORY OF RANGE USE BY LIVESTOCK

It is not possible to understand the impacts of animal husbandry on Baja California's wildlife without reviewing the history or ranching in the state. Right after colonization, cattle was ranched on open ranges, but throughout the 20th century, it was limited every time more by agrarian policies leading to a fractioning of land ownership. Although such fractioning was intended to alleviate social problems and enhance agricultural production, its results have been contradictory in terms of productivity, range conservation and impacts upon wildlife. We have divided the history of animal husbandry in the state into 4 periods. These are overlapping to some degree and surely escape the rigor of the historian, but reflect, to our best understanding, the major events in the human-environment relationship mediated by livestock.

3.1. Mission period

The first livestock arrived at the Peninsula on 3 May 1535 when Hernan Cortés disembarked some horses at the Bahía de Santa Cruz (currently La Paz). The mission of Loreto, the first permanent mission of the Peninsula, was established in 1697, and its inventory included 30 cattle, 10 sheep, 8 goats, 4 pigs and 1 horse. In 1683, Almirante Isidro Atondo y Antillón and the Jesuit priests Eusebio Kino, Matías Goñí and Juan Bautista Copart founded the mission of San Bruno (about 40 km north of Loreto), for which they received cattle from what are now the states of Sonora and Sinaloa (Martínez-Balboa 1981). This fact of receiving livestock from across the Gulf of California became common practice, as the animals raised on the local missions were employed for the northward expansion of the mission system (Del Barco 1973). So, the mission of Loreto received 8 cows and 6 horses in 1698, from Sinaloa, and father Kino sent an additional 200 cows and 170 horses from several Sonoran missions in 1700.

It is difficult, based on the information available, to determine the herd of each mission throughout time. For example, Francisco Palau reported in 1772 that there were fewer than 650 head of cattle in the missions from Santa Gertrudis to Santa María, but in 1800 the Dominican fathers reported almost 5,000 cattle at the El Rosario and San Miguel missions. In 1834 there were reportedly 3,500 head of cattle at El Descanso mission alone, while the mission of Nuestra Señora de Guadalupe reached over 5,000 cattle (Acosta 2009).

3.2. Consolidation

With the decline of the mission period of Baja California, between 1818 and 1849 (Acosta 2009), the existing agriculture all but disappeared and the ranches in the northern part of the Peninsula became the major economic endeavor of the residents. So, in 1827, between the mission of Santo Tomás and Todos Santos, the valleys and hills were "covered" by cattle, horses, and mules. In San Miguel, the mission had 3,000 horses and mules, and 30,000 sheep on the Buenas Aguas ranch (Pattie 1831). Also, on mission lands between El Rosario and Santo Tomás there were, before 1948, 60 000 cattle, 7,000 horses, 200,000 sheep, 2,000 mules, 2,000 burros, and 20,000 goats (Browne 1869).

During the first half of the 19th century several marginal ranches were established in the Central Desert, as the young married and became independent from their families. These were relatives of soldiers who now were idle in the region (Lassepas en Henderson 1964). It appears that over 150 ranches were established between Guadalupe and San Borja, but normally only a third were occupied at any time (Aschmann 1959). The climatic pattern of seasons of good, or even copious, rains punctuated by long periods of drought made ranching an hazardous activity and many ranches failed, some even before a year had elapsed. However, when a series of good years caused increases in livestock numbers, idle ranches were re-occupied or new ones established. When a new drought struck, only those in the best places survived (Aschmann 1959). Rancho Paraíso established by the Jesuits of the San Borja mission at a site explored by father Fernando Consag (1751) was abandoned in the fall of 1949 for lack of forage (Aschmann 1959). The severe, and widespread drought of 1863–1864 caused the loss of most of the sheep, horse, and cattle of the large herds of the missions (Browne 1869).

The economic activities of the region were affected by the anarchy that reigned until 1877, when the first stable government lasting a long period was established (Henderson 1964). Besides, before the late 19th centruy the region was not very attractive for productive enterprises (Minnich and Franco-Vizcaíno 1998), and it was until after 1850 when a large demand for meat [and surely hides and tallow as well] began to develop due to the mining boom in Upper California (Minnich and Franco-Vizcaíno 1998), and by 1857 there was already a large demand for meat leading to the development of ranching at ¨la frontera¨ (Henderson 1964). At this time there were 43 livestock ranches on 77 "sitios de ganado mayor" ("sites of large livestock;" aprox. 135,000 ha) that had about 8,260 head of cattle (Lassepas en Henderson 1964). The demand of cattle-derived products by miners continued to stimulate ranching in northern Baja California and in 1911 there were 21,000 head of cattle in association with the two northern sierras (Juárez and San Pedro Mártir; Henderson 1964). Some earlier reports speak of as many as 25,000 heads of cattle in the Sierra de San Pedro Mártir alone (Minnich and Franco-Vizcaíno 1998). Not only were animal products exported, but some California ranchers traveled south to buy live cattle, as the travels of Joseph E. Pleasants from Los Angeles, Calif., to San Telmo in 1867 and 1868 testify (Pleasants 1965).

In northwestern Baja California, during the late 19th and early 20th century cattle foraged in the lowlands until grasses were dry, after which cattle moved, reportedly of their own volition, to the higher mountains to forage on the meadows of the Sierra San Pedro Mártir, coming down again forced by the cold of autumn. Such transhumant cattle was reportedly in better condition that those that did not move to the upper meadows (Pleasants 1965). Irrespective of this, the quality of the cattle was influenced heavily by rainfall. Both of Pleasants trips were in unusual years and cattle were in good condition, and were able to walk all the way to the "Los Nietos" ranch at a pace of 20 miles/day. However, as happened often, the following year was a bad year, in which ranchers lost most of their cattle, and Pleasants did not return south.

Although the increase in cattle numbers in the northern end of the Peninsula at the end of the 19th century has been attributed to the emergence of the California market for cattle products, we believe that it might have been favored by the presence of alien herbs. These herbs, which evolved under grazing pressure in the old world, colonized the region during mission times and could have provided much of the primary productivity of herbs and grasses (see review in Minnich and Franco-Vizcaíno 1998).

During the "Porfiriato" (the series of succesive presidential terms of Porfirio Díaz in the late 19th and early 20th centuries), many of the best agricultural lands, which had been covered by grass, were plowed for farming, including the San Rafael (Ojos Negros) and San Vicente valleys which were turned over to barley (Henderson 1964).

3.3. Large livestock enterprises

During the second part of the 19th century, Mexico pushed forward a colonization strategy to increase the population and development of parts of Baja California (Walther-Meade 1983). As a part of it, land grants were given out to individuals and private companies to occupy and exploit idle lands (lands not under occupation and belonging to the Country). Such grantees were able to recruit only a few colonizers, which were left stuck on remote desert lands (Walther-Meade 1983). On the other hands, the first grantees tried to maximize their income by transferring their holdings to foreigners, or at least to associate with them. The purpose of the colonization policy were, hence, distorted by the land winding up in the hands of companies that eventually got a hold of almost all of the current state of Baja California.

These colonization policies began at the end of the century, because as of 1870 there were no records of lands assigned to names that later reflected the existence of large companies, and all grants of land were to persons with Spanish surnames, and properties were small (Shipek 1965). Afterwards, large cattle companies under foreign (U.S.) landholders were created. For example, Robert H. Benton established one of the most famous such ranches, the Circle Bar Cattle Co., which had large tracts of land in the southern part of the Sierra de Juárez and nearby areas. from 1913 to 1920, it was administered by Robert's son Roy, who even imported shorthorn steers from Scotland to improve his herd of 10,000 head (fttp://animalscience.ucdavis.edu/memorial/benton.htm, accessed 5 January 2010). Afterwards, the company was administered by Ralph S. Benton, and it included cattle, sheep and horses which were raised on lands leased from the government, and moved according to forage availability. Between 1924 and 1930 the Circle Bar rented more than 40,000 ha on its own name, and 35,000 ha to dummy tentants, concentrated mostly on the Sierra Juárez and lands to the south (Samaniego-López 1999).

Another cattleman, Newton "Newt" House, had lived at the Rancho de [San Rafael de] Yorba, since 1894, where he worked for the Circle Bar and at the same time gathered a herd of his own and, eventually, formed his own company, under which he leased and bought large tracts of land (Samaniego-López 1999). Newt House prospered during the governorship of Abelardo Rodríguez (1923–1929) and was, in general, well supported by the system. During property conflicts, for example with the Ramonetti, the Secretaría de Agricultura y Fomento (the Ministry of Agriculture and Promotion) gave him "special treatment" (Samaniego-López 1999). Newt obtained Mexican nationality in 1924, and became safe from extraditions.

The area where these ranches were established represents a very important part of the mayor cattle and sheep producing area of Baja California, namely the northwestern part, between San Quintín and the U.S. border, and from the coast to the peninsular divide. In 1911, 12,000 cattle were reported from the Sierra de Juárez and 9,000 from that of San Pedro Mártir, along with small herds of horses (Flores and González 1913), whereas in 1918 between 18,000 and 20,000 head of cattle were calculated in the same area (Nelson 1921). There were also smaller operations and, for example, at the Rancho Los Pocitos, its Spanish proprietors raised sheep and fleece goats (Flores and González 1913).

Although large cattle companies were the major form of land administration in northwestern Baja California, they were not exclusive to it. Large cattle companies were the proprietors of most of the cattle in the Valle de Mexicali and the southern portion of the Colorado River delta in the early 20th century, where the most common livestock was cattle, but there were also good numbers of sheep for the production of wool. At this time, it was already anticipated that agriculture would encroach upon livestock ranching in the future (Bonillas and Urbina 1913). For its part, the Magdalena Bay Co. held thousands of cattle on the Magdalena plain and nearby lava fields (Nelson 1921). The rest of the Peninsula had little cattle, whose numbers fluctuated in an abundance-scarcity cycle matching the cycle of rainy-dry years (Nelson 1921).

as in previous decades ranching in the northern portion of the Baja California Peninsula in the early 20th century was mostly for export of meat and hides, and the most important ranges were the higher parts of the sierras, especially that of San Pedro Mártir (B√se and Wittich 1913; Flores and González 1913).

The other important livestock component of northern Baja California was sheep, although they were raised in large numbers only in the northwest. During the 19th century foreign investors organized transhumance runs of sheep, mostly herded by Basque herders, which started their foraging journey near Tijuana in August, herding the sheep to the upper meadows of the Sierra San Pedro Mártir, from where they returned in October (Henderson 1964). This practice is thought to have increased in 1910, when sheep grazing in the meadows of the sierras of southern California was prohibited (Minnich 1988, Minnich et al 1997). However, by the same time, 6,000 sheep on the mesas south of Tijuana were considered a pale remembrance of times past, at least compared to the observations by James Ohio Pattie, a renowned mid-19th century trapper (B√se and Wittich 1913).

We have no record on whether sheep transhumance starting in the Tijuana mesas lasted long or not, but during the mid-20th century up to 20,000 sheep were taken annually to graze the meadows of San Pedro Mártir (Minnich *et al.* 1997; SEMARNAT 2009). This practice was prohibited in the mid-1960s following pressure by cattle growers of the area (Meling-Pompa 1991, SEMARNAT 2009). Currently, these meadows receive a variable grazing pressure, in response to resources elsewhere. In 1987, following a rainy winter, they were used little by cattle, but during the 1988–1990 drought they were heavily grazed (Minnich *et al.* 1997; SEMARNAT 2009).

3.4. Agrarian reform

One of the major transformations of modern Mexico, as far as land use goes, was that given through land re-distribution in the form of ejidos, communal land allotments that, until recent legal reforms, could not be sold. These commenced during the term of president Lázaro Cárdenas (1934–1940), and continued with ups and

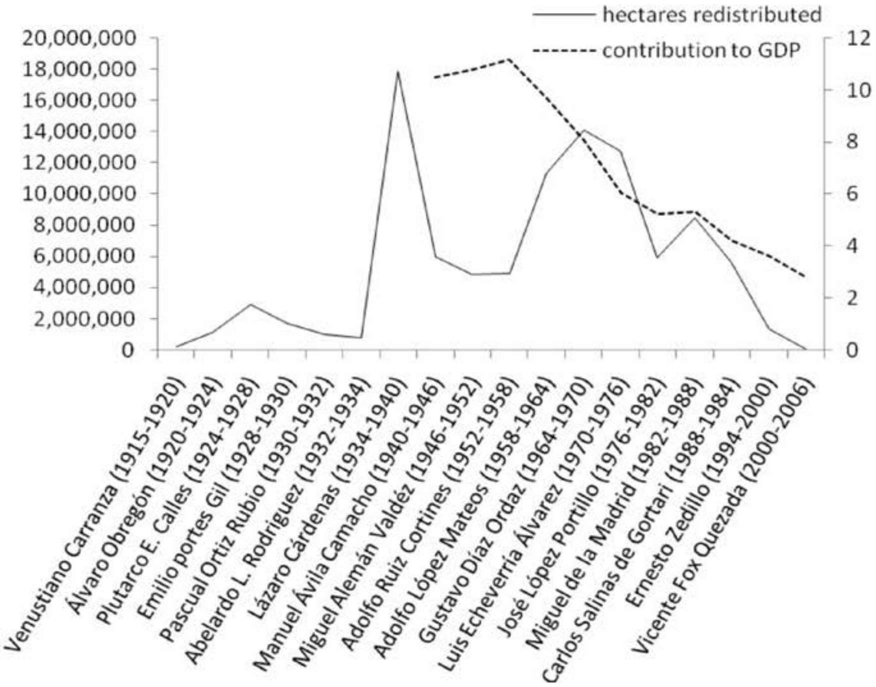

FIGURE 3. Land re-distribution and contribution of agriculture to the Gross Domestic Product (GDP) after the Mexican Revolution.

downs, until the term of Carlos Salinas de Gortari (1988–1994; see Figure 3). This re-distribution of land, which provided land to landless peasants did not significantly enhance the national economy, but had environmental effects, like soil erosion and loss of biodiversity in areas that probably should have never been converted to agriculture (Méndez 2006; FAO 2000).

This re-distribution caused fractioning of the land into smaller units, with more landowners, and a concomitant change in the patterns of livestock grazing. Gradually, the movement of livestock in search of forage was prevented by fences, and grazing pressure increased in many areas (although some ejidos, especially in the Baja California Peninsula still have large tracts of open range). Although most of the smaller properties were now fenced on the periphery, no internal fences were constructed to apply rotational grazing schemes that allow for restoration of range productivity and maintenance of biodiversity. On the other hand, during the second half of the 20th century, land leasing for grazing has been common in the northern part of the Peninsula, again leading to the creation of cattle companies. We lack information to judge whether this has alleviated grazing pressure locally, or it has increased it.

The situation further south can be exemplified with the few data for the state of Baja California Sur (the southern half of the Peninsula). Soon after land re-distribution began, that state inventoried 48,647 cattle, 5,173 horses, 4,622 goats, 3,044 mules, 2,615 pigs, 2,214 sheep, and 1,944 burros (Martínez 1947). The cattle were for local consumption, as meat, and export of hides, dried salt meat, and ranch cheese. During the second half of the 20th century, somehow favored by the re-distribution of the land, goat numbers increased notably throughout the arid portions of the Peninsula, especially in Baja California Sur. At the end of this century, goats were the main livestock in the Vizcaíno Desert area, and were the mainstay of over 200 rural communities there (Castellanos and Mendoza 1991).

4. RANCHING PRACTICES

4.1. Burning

For thousands of years, humans have intentionally burned native habitats in the Peninsula (Consag, 1751; Aschmann 1959, Biswell 1999), and not long ago this was still commonly practiced by ranchers between October and December to increase the forage value of chaparral (Meling-Pompa 1991; J. Contreras and E. Mellink, unpublished observations). This practice was, however, indicated as one of the two major problems that arboreal vegetation faced in the region (Engerrand and Paredes 1923), although it was not clear whether this opinion was backed by objective data. On the contrary, controlled burning, by rejuvenating and opening to herbaceous plans old, lignified chaparral stands, can be highly beneficial for cattle as well as for wildlife (Biswell 1999).

4.2. Transhumance

At the onset of the 20th century, as in the previous centuries, the range was essentially open for cattle to roam and graze, both in the Sierras and the desert (Acosta 2009). At this time, in northwestern Baja California cattle were not managed, but kept "in a wild state…" in which "… the animals roam around on the range and the owner does nothing else but branding them" (Flores and González 1913), which resulted in strong fluctuations resulting from the variable availability of forage. However, this view is, at least, simplistic, since as long ago as the 1790s, cattle were kept on the lower plains during most of the year and herded to the upper meadows of the Sierra de San Pedro Mártir in summer (Henderson 1964). This transhumance was the sign of animal husbandry in the northern part of the Peninsula during the 19th and 20th centuries. Even when cattle husbandry included little more than branding, like at San Isidro del Mar in the early 20th century, they were moved to different ranges, which could include leased ones (Samaniego López 1999).

Likewise in Sierra de Juárez, livestock grazed Valle de San Rafael valley (currently Valle de Ojos Negros), Real del Castillo, and Valle de la Trinidad during most of the year, and were herded to the Laguna Hanson area for the summer. Newt House's operations eventually included up to 10,000 cattle under this scheme, between Real del Castillo and Valle de la Trinidad, and Laguna Hanson (Acosta 2009). Even in less suited areas, like ranges in Baja California Sur, Indian livestock, including horses, mules, burros, and cattle, were kept free on the range, but herded to the upper parts of the sierras during periods of drought, in the early 20th century (Diguet 1912).

Transhumance could be variable and might include areas not usually grazed, upon opportunity, as exemplified by the picturesque Antonio de los Ángeles López Meléndrez (a.k.a. "El Oso" ["The Bear"], deceased on the range in 1943), A cattleman for over 20 years at the turn of the 20th century. In good years, when there was grass and water in the desert, to the east of the Sierra San Pedro Mártir, the cattle were driven to the Colorado River (a one-month drive), and back. However, before the early 20th century, there were no known reliable watering places, as places were water occurred were known only by Indians. The discovery and enlargement of the Tres Pozos well by Edward W. Funcke, another picturesque character, created a reliable water source, allowing for such drives to the desert (Humphrey 1991; Mellink 2000).

Large-scale transhumance concluded with the agrarian reform initiated by president Lázaro Cárdenas in the 1930s. So, the creation, and allotment of land to ejido Sierra de Juárez resulted in the interruption of Newt House's transhumance ranching (Jesús José Arenivar Salgado Pers. Comm.). Although the larger-scale operations ceased, local transhumance continued to be practiced when the properties allowed for it. For example, it was so important for the ranchers of San Telmo and Santo Domingo, on the lower west slope of the Sierra de San Pedro Mártir, that "… it is impossible to raise livestock [without] grazing San Pedro Mártir" (Meling Pompa 1991), where cattle were kept from May and June to late October. This form of transhumance continued until well into the 20th century (Meling Pompa 1991, Minninch *et al.* 1997, Minnich and Franco-Vizcaíno 1998).

4.3. Harvesting of native plants for forage

Although most of the time cattle were left to survive the vagaries of climate on their own, when severe droughts struck they were fed often with wild plans harvested specifically for that purpose. These plants included cacti, like barrel cacti (*Ferocactus* spp.) and cardón (*Pachycereus pringlei*), foliage and pods of leguminous trees like mesquite (*Prosopis* sp.) and dipua (*Parkinsonia microphylla*), and even trunks of the boojum (*Fouquieria columnaris*) and floral stalks of maguey (*Agave* sp.) (Diguet 1912, B√se and Wittich 1913). During the 1893–1894 droughts, barrel cactus near La Paz were so exhausted by harvesting that special trips were made to the nearby islands to bring more (Diguet 1912). Harvesting of native plants as emergency forage is still practiced throughout the Peninsula (J. Contreras and E. Mellink, unpublished observations). For example, although oasis-based cattle roam the ranges most of the time, during the dry part of the year they are confined to corrals where their forage includes native plants harvested from the wild, like choyas and barrel cacti (Breceda *et al.* 1997)

4.4. Ranching policies in times of drought

During strong droughts the government subsidizes ranchers with forage. Although such programs succeed in preventing the death of cattle due to lack of food, they contribute to maintain many more cattle than what the carrying capacity of the range allowed for. Another program that is often established in times of drought is that of subsidies to build large watering tanks for cattle, although their value for the production of cattle is dubious.

5. EFFECTS OF RANCHING ON RANGELANDS

Although Minnich and Franco-Vizcaíno (1998; see also Sosa-Ramírez and Franco-Vizcaíno 2001) were cautious in determining the magnitude of the impact that ranching has had on native habitats, we believe that it is possible to speculate on some of its likely effects on wildlife. Most of our inferences should be taken as propositions for investigation, rather than as proven facts.

Although we are unable to establish precisely the effects of ranching on wildlife, it would be highly unlikely, close to impossible, that there were none, given the known, strong impacts elsewhere (Noss 1994), which include "…loss of biodiversity; lowering of population densities for a wide variety of taxa; disruption of ecosystem functions, including nutrient cycling and succession; change in community organization; and change in the physical characteristics of both terrestrial and aquatic habitats" (Fleischner 1994; Belsky et al 1999). In particular, grazing by cattle lowers density and structure of the vegetation and seed production; and compacts the soil, lowering water infiltration, increasing erosion, and modifying its available oxygen, chemical composition, microorganisms, and fertility (Liacos 1962; Belsky et al 1999; Rauzi and Smith 1973; Gonnet *et al.* 2001; Czeglédi *et al.* 2005). However, the severity of the impacts varies with type of ecosystem, species of domestic grazer, and the particular wildlife species of interest (Allen 1986).

5.1. Effects of overgrazing on wildlife

During the last two decades anyone visiting the meadows of the Sierra de San Pedro Mártir would have found a very short herbaceous community, which would have contrasted with the dense and tall grass cover found by Ed Griffin in 1887 and D.K. Allen in 1888 (Minnich and Franco-Vizcaíno 1998), and by L.M. Huey in the 1920s (unpublished field notes, San Diego Natural History Museum), and a paucity of wildlife that contrasts with its abundance in 1905–1906 (Nelson 1921). The change in the plant community has as its obvious cause overgrazing, which has "… reduced the diversity and abundance of native grasses… has caused soil compacting and degradation of the hydrologic and biologic systems" (SEMARNAT 2009). It has been argued that the culprit of such overgrazing of the meadows were the sheep on a transhumance scheme (Meling-Pompa 1991), although cattle herds found in them sometimes appear to exceed easily the 15–20 ha/ animal unit of recommended carrying capacity (Henderson 1964; COTECOCA 1985). Causes for the impoverishment in the wildlife of these meadows are more difficult to establish, and hunting might explain some of it. However, habitat degradation due to overgrazing is possible a major cause.

Regrettably, the issue has been investigated only scantly. A few decades ago some cattle exclusions were established in one of the meadows. After only four years, forage production was 50% higher inside the exclusions than outside them, and it was thought that longer exclusion periods appeared to lead changes in plant composition, and suggested the possibility that some plants species were eradicated due to grazing (Minnich and Franco-Vizcaíno 1998).Likewise, a 10-yr exclusion of cattle resulted in increased plant species richness and recruitment and chages in its vegetation structure, in the tropical dry forest of the tip of the Peninsula (Arriaga 2006).

If our hypothesis is correct, and we believe it is, locally, the most obvious effect of grazing appears to be the meadows, although evidence is circumstantial. Disappearance of the Rosarito de Loya meadow was a dramatic case that can be in all likelihood attributed to overgrazing, although the exact drivers, and their relative weight, are not known. This is not the only case of a 20th century disappearance of a meadow. A decade ago, the meadow of Rancho San Pablo, in the northern slope of the Sierra de San Pedro Mártir, was drying up because of the lowering of it water table due to the creation of deep erosion trenches (J. Contreras and E. Mellink, unpubl. obs.). The causes behind the formation of gullies were not clarified, but the meadow and nearby slopes had been grazed heavily for decades. Another meadow that disappeared, although we lack knowledge on the events leading to it, was that of Rancho Tepi (in Ejido Tepi, northern San Pedro Mártir). A fourth example is provided by the grassy river-bank of Valladares. In 1996 E. Mellink and J. Luévano (Unpubl. data) searched for it in vain, and although they found its probable location, there were no traces of it. In 2013, we found its probable location, but the site was covered by shrubs, rather than grass and forbs.

The animal species most affected by the deterioration and loss of meadows is probably the California vole, which was trapped commonly in most meadows of the area in the early 20th century, and was absent at most sites in the mid 1990s (E. Mellink and J. Luévano Unpubl. data), despite it being a resilient species that can even become a pest in certain agroecosystems in California. It is our impression as well (J. Contreras, unpub. obs.), that overgrazing of the meadows has caused a reduction in forage available to mule deer.

Outside the grassy meadows, evidence for overgrazing is even more scant, although given that such effects have been documented throughout the world it would be naive to think that they did not exist in Baja California. Indeed, one author (Martínez-Balboa 1981) commented that, in general, rangelands in Baja California Sur were overgrazed, while another (Parra in Castellanos and Mendoza 1991) indicated that those in El Vizcaíno were possibly overgrazed. A brief study with cattle exclosures was inconclusive about grazing impacts on the forest range on the Sierra San Pedro Mártir (Minnich and Franco-Vizcaíno 1998), but time could have been too short.

Overgrazing of dry ranges possibly has impacted negatively some populations of mule deer, has it has done in southwestern United States (Lott, *et al.* 1991; Heffelfinger *et al.* 2006). The population of the endangered peninsular pronghorn antelopes (*Antilocapra americana peninsularis*) in the center of the Peninsula was subject to heavy hunting to supply meat to nearby mining camps (B√se and Wittich 1913). Although protected, this population has not bounced back to its historic numbers. No answer of this exists as yet, but it is possible that range degradation because of overgrazing is involved (see, for example, Schmidly 2002). Overgrazing can affect the quantity and quality of forage for pronghorns, (Howard *et al.* 1990), and the survival of their fawns (Autenrieth 1982). In some areas California quail (*Callipepla californica*) could have been affected by overgrazing, as happened in northern California (Leopold 1977).

Effects of the presence of livestock on a certain animal species can be related to the livestock species using the range. For example, Lee Grismer (Pers. Comm.; La Sierra University) did not perceive an effect of cattle upon reptiles, but where goats were present, reptile communities were very poor.

Grazing can impact wildlife without livestock being present year-long. Both, heavy periodic impacts and cattle present during critical periods like droughts, might be enough to affect wildlife. So, periods of heavy grazing in the northern sierras could negatively impact the feed or cover for mountain quail (*Oreortyx pictus*; Brennan 1994; Belding in Gutierrez and Delehanty 1999; Miller in Gutierrez and Delehanty 1999). Likewise, the yearly pulses of sheep grazing might have affected bighorn sheep (*Ovis canadensis*), and, indeed, its distribution during the 20th century could have been an artifact of previous grazing by domestic sheep. Mule deer are probably impacted more heavily when heavy grazing coincides with drought periods (Heffelfinger *et al.* 2006).

One of the habitats that might have received an especially heavy blow from grazing is the understory of riparian forests. In Baja California, this has very likely negatively impacted the California Bell's vireo (*Vireo belli pusillus*; Brown 1993). Another effect of the grazing of understory is the loss of adequate cover for the hiding of mule deer, especially the fawns (Loft *et al.* 1987). In some areas, high concentration of cattle could have affected the population of certain burrowing rodents, for example the moles *Scapanus latimanus* and *S. anthonyi* (both in the Mexican list of species at risk) in the northern sierras of the Peninsula.

5.2. Other effects of ranching on wildlife

Interference competition between livestock and wildlife can happen, although it is difficult to detect, except for selected situations. For example, feral burros have been argued to exclude bighorn sheep from waterholes (McKnight 1958), although the evidence for this is diffuse (Krasuman *et al.* 1996). Ticul Álvarez (in Mellink 1996) thought that this was the case in Baja California as well.

Besides direct competition through interference, there are a number of indirect effects of animal husbandry on wildlife. One of them is intentional burning. In addition to benefiting livestock, in California burning of an old stand of chaparral can benefit many species of mammals and birds (Longhurst 1978), including California quail and mule deer (Sommer et al 2007). Although the effects of such burns in Baja California have not been studied, they are very likely similar.

One issue for which evidence is more solid is that of transmission of diseases and parasites from livestock to wildlife, whether livestock are the original carrier or that they become an effective intermediary. This has been one of the most serious conservation problems of bighorn sheep in the southwestern United States, and often the presence of pathogens is the only factor preventing the restoration of bighorn sheep populations (Goodson 1982; Berger 1990; Krausman *et al.* 1996; Schommer and Woolever 2008). In Baja California, diseases and parasites present in cattle have been found in mule deer (Contreras *et al.* 2007). Pronghorns are also susceptible to livestock diseases (Thorne *et al.* 1988), and perhaps this has also played a role in the failure to populations in the central Peninsula to rebound, although this has not been investigated.

Some wildlife species rely on succulent plants in times of drought, including pronghorns (Funcke 1919), mule deer, bighorn sheep, and jackrabbits. Hence, the harvesting of such plants to feed cattle can impair the habitat to support the native species.

Grazing impacts upon wildlife habitat are probably aggravated by governmental programs that prevent cattle die-offs on the range during drought times by promoting high stocking rates, surely in excess of the range's carrying capacity at that time. In the long run, these programs, rather than favoring the cattle industry are probably counterproductive, as well as negative for habitat and wildlife conservation.

Finally, in addition to maintaining large stocking rates on the range, governmental programs affect the habitat through the building of large watering tanks that concentrate cattle and create high impact zones around the tanks. This results in areas which are compacted and cleared of vegetation by the cattle; with soil erosion as a possible consequence, in addition to the direct effect upon the habitat. So, even though additional water sources could benefit wildlife, these large tanks fail such purpose. If such programs call for watering tanks, it would be more appropriate to build small ones dispersed throughout the range and designed so that wildlife can benefit from them.

6. COROLLARY

The precise impacts of ranching on wildlife in the Peninsula of Baja California will never been known. It can be reasonably assumed that during the Mission period these were few and localized, whereas those by transhumance could have been heavier, especially that of sheep grazing in the northwest, at least at some habitats. Also, land re-distribution through the agrarian reform, by preventing the rotation of cattle on the range, possibly resulted in a more widespread and heavier overgrazing of the range.

It seems likely that ranching impacts have affected populations or whole subspecies, but not the entire population of a species. For example, it is possible that at one time there were voles in all meadows, perhaps as meta-populations, but by the time Huey (1964) surveyed the mammals of the Peninsula, they were already impacted by grazing and were present at only the few sites at which he documented them. In this case, although the species is nearly eradicated from the Peninsula, and apparently two of the three subspecies described by Huey (1964) might already be extinct, the California vole as a species is not at risk; it is even a pest at many California sites. On the other hand, chaparral burning to benefit cattle is possibly beneficial for a number of wild species. The more complex relationship of grazing-soil erosion—increased runoff and its biological repercussion merits careful scrutiny and research, as it is a potential driver of future environmental degradation.

While gathering information for this chapter it became evident that there was a notorious blindness toward the possibility of grazing impacts upon the range. As a consequence, range restoration is absent from the local official programs in support of ranching or those for environmental conservation. The 2001 publication of the Mexican Official Norm that regulates range restoration (NOM-020-RECNAT-2001), by raising the issue, gives some hope that reversal of grazing impacts will eventually permeate local programs.

Although the evidences of ranching upon wildlife and its habitat in the Peninsula of Baja California are scant, we feel that they point at a real problem, and that range degradation, including soil erosion and changes in the plant communities, should be paid attention to. We believe that an objective and careful assessment of the condition of the range is not only convenient, but imperative, both by a think tank group, and through field research. Among other things, the surveys carried out 30+ years ago by the Comisión Técnico Consultiva para la Determinación de los Coeficientes de Agostadero, COTECOCA—could be rescued and repeated now. Official programs in support of ranchers should pay much more attention to range restoration (of course with native plants) than to forage provisioning and construction of large watering tanks. Those wildlife species (and native plants, if any) likely to have been impacted by ranching should be targeted for specific conservation actions.

If ranges continue to deteriorate, the environmental as well as consequences for ranching will be severe. However, unless agriculture officers, ranchers, and scientists recognize overgrazing as a problem, little will be done to revert from the impacts that have already occurred, and prevent future land degradation from ranching. Addressing the issue of grazing impacts on the land would lead to better ranges for cattle and better habitat for wildlife.

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THE NORTHWESTERN LIMIT OF MANGROVES IN MEXICO: ENVIRONMENTAL LESSONS FROM AN ACCELERATED COASTAL DEVELOPMENT

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The northwestern region of Mexico is among the most productive and biodiversity-rich areas of the world, which has provided ecological services to humans since pre-Hispanic times and continues to provide them today. Mangrove ecosystems in this region are fundamental to maintain the coastal environmental quality. They also provide nutrients that sustain marine and terrestrial species, many of which have economic importance. However, mangroves and their surrounding environments are being impacted by the growth of coastal populations and the development of economic activities in this region. To observe and understand how human patterns and processes have affected mangrove ecosystems through time and evaluate the consequences that unplanned development activities have had in Sonora and Baja California Sur, we integrated historical information, aerial photography and field surveys. We register how these landscapes have gradually changed over the last century as human development progressed. In areas that have been developed for longer periods of time, like the southern region of Sonora, mangrove ecosystems have been drastically modified and important ecological functions provided by these ecosystems, like the once rich fisheries, have vanished. On the other hand, in areas where development is still scarce, like some in the Pacific coast of Baja California Sur, mangrove ecosystems present suitable environmental conditions and still provide vital services to human populations.

1. INTRODUCTION

The waters and coastal environments of the Sea of Cortés in the arid northwestern Mexico, constitute one of the most productive and biodiversity rich areas of the world (Sala *et al.* 2004, Enriquez-Andrade *et al.* 2005). This region has provided environmental services to the human populations that have inhabited the coastal areas of the present states of Sonora, Baja California Norte and Baja California Sur for millennia (Almada 2000, Del Río and Altable-Fernández 2000).

Human societies have been part of these natural environments, and have exerted different pressures on its ecosystems with an ever-increasing trend for a long time. Currently, this coastal region is inhabited by almost ten million people and has one of the highest population growth rates in the country (INEGI www.inegi.org.mx). Such demographic growth results from the different opportunities that the waters and coastal environments of the Sea of Cortés provide to develop economic activities. Waves of immigration from regions with agriculture and/or livestock practices have and are currently settling in the area searching for alternative economic incomes. As this human expansion continues, economic activities are exerting development pressures that have transformed the natural environmental conditions compromising the integrity of several ecosystems and their capacity to provide environmental services (Enriquez-Andrade *et al.* 2005, Glenn *et al.* 2006).

The presence of mangrove ecosystems in these arid regions is essential to sustain the environmental quality of the coastal ecosystems and improve the quality of human life (Holguín *et al.* 2006, López-Medellín *et al.* 2011). The intricate structure of their roots and stems provide habitat to several marine and terrestrial species, many of which have economic importance and/or sustain fisheries (Aburto-Oropeza *et al.* 2008); their canopy provides stopover sites for migrating species and can sometimes be the only green vegetation available in the arid landscape (Palacios and Mellink 1995, Whitmore *et al.* 2005); the high production of organic matter intrinsic to these ecosystems contributes with large quantities of organic matter and nutrients to both land and sea (Flores-Verdugo *et al.* 1992, Holguín *et al.* 2001, Félix-Pico *et al.* 2006); they also remove contaminants by incorporating them in their tissues or immobilizing them in sediment (Feller *et al.* 1999, Rivera-Monroy *et al.* 1999); mangroves and their vicinity also provide appropriate environments for the development of aquaculture (Páez-Osuna *et al.* 2003) and constitute scenic landscapes that are suitable for recreational and tourism activities (Presenti and Dean 2003).

The waters and coastal environments of the Sea of Cortés constitute ideal places for the development of economic activities that are attracting a large population to settle on its coasts with ever increasing development pressures that are transforming the natural environments and their capacity to provide ecosystem services (Enriquez-Andrade *et al.* 2005, Glenn *et al.* 2006).

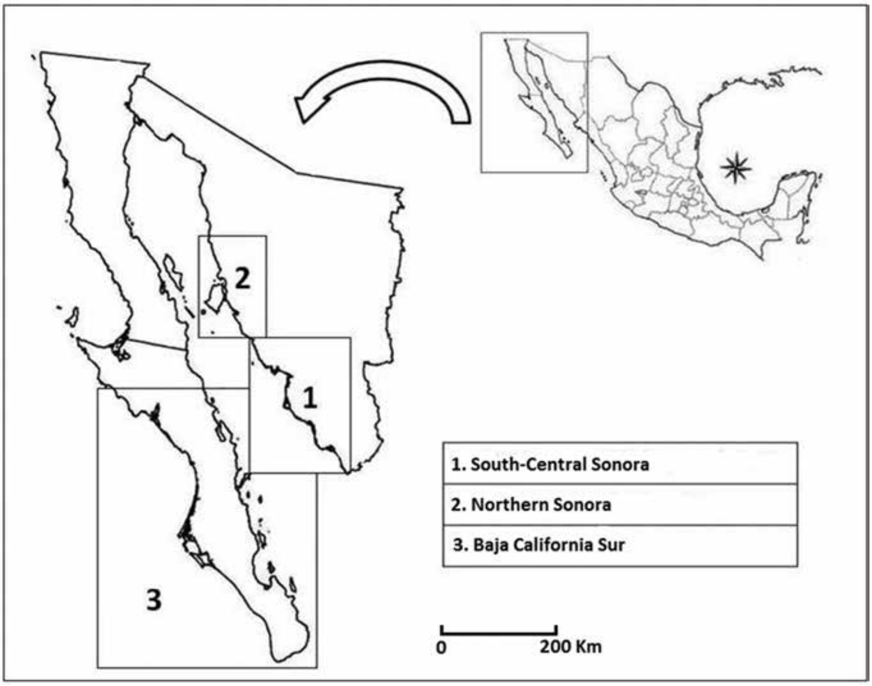
Furthermore, the urgency to generate rapid economic growth in Mexico has historically promoted policies that focus on economic gain by encouraging the development of hastened practices to maximize short-term yield, rather than harvest resources in a sustainably fashion (Young 2001, Basurto 2005). This situation has had negative impacts on both coastal ecosystems and human populations, because it threatens the different ecosystem functions, services and economic values from which the region and its population benefit (Enriquez-Andrade *et al.* 2006, López-Medellín *et al.* 2011). Therefore, it is of the outmost importance that the degradation of natural environments is reduced or reversed, so that the future population can enjoy the benefits of these coastal ecosystems.

In order to understand and assess how human patterns and processes have influenced mangrove environments through time, and also to inform land management decisions about activities that highly degrade natural environments, we combine historic data with current information and local environmental and socioeconomic data in this manuscript and provide a summary on the history of the human populations and the economic developments in the coasts of the arid territories in northwestern Mexico in order to illustrate the environmental consequences of unplanned development activities.

By visually comparing historic aerial photographs with modern imagery, we provide reference frames of times when natural ecosystems were less affected by humans and examine how the accelerated development has claimed coastal environments; finally, by performing assessments of the current environmental conditions of all mangrove localities in Sonora and Baja California Sur (BCS) we explored the long-term anthropogenic changes and their impacts on natural habitats. We hope that this regional synthesis of material and political environmental history will serve as a starting line to further develop this kind of studies in this part of the world.

In order to organize our work, we divide the area into three regions according to the historical development of human population and economic activities (see Figure 1):

1. South-central Sonora. A region with many wetlands influenced by deltas of large rivers. Has higher population density that practiced agriculture, cattle, mining, fishing and trade since the 18th century (see Figure 2).
2. Northern Sonora. Has lower population density, its development largely related to a fishing expansion in the 20th century (see Figure 3).
3. Baja California Sur. Has the lowest population density, few merchant ports and small settlements that were created in the 20th century with the expansion of fishing (see Figure 4).



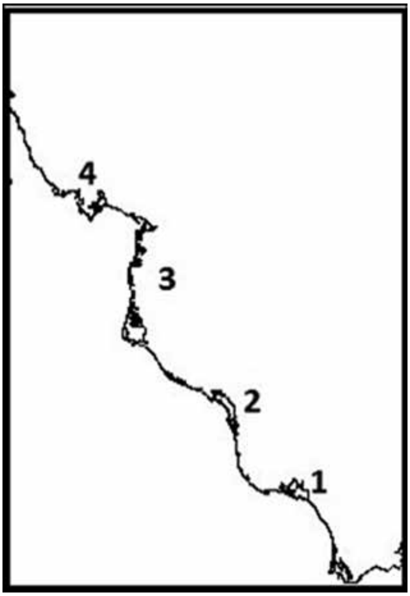


FIGURE 1 (ABOVE). Division of northwestern Mexico according to the historical development of human population and economic activities. FIGURE 2 (BELOW). South-central Sonora. 1. Yavaros-Moroncarit system, 2. Estero Tobari, 3. Las Guasimas-Estero Lobos system, 4. Guaymas.

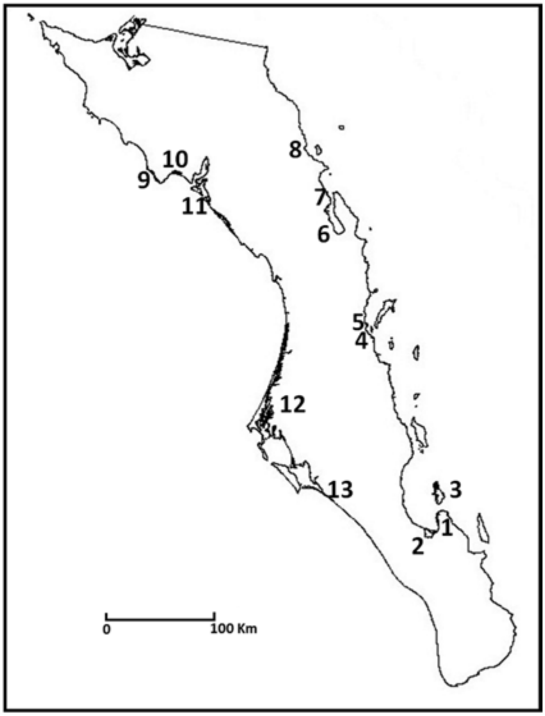


FIGURE 3 (ABOVE). Northern Sonora. 1. Estero Tastiota, 2. Estero Santa Cruz, 3. Seri estuaries, 4. Estero Sargento. FIGURE 4 (BELOW). Baja California Sur. 1. Bahía Balandra-Estero Enfermería, 2. La Paz-El Mogote, 3. Isla Espíritu Santo, 4. Puerto Escondido, 5. Loreto-Nopoló, 6. Bahía Concepción, 7. Mulegé, 8. San Lucas, 9. Estero La Bocana, 10. Estero El Coyote, 11. Laguna San Ignacio, 12. Bahía Magdalena-Bahía Almejas, 13. Estero Rancho Bueno.

2. MATERIALS AND METHODS

The historical development of human activities in the states of Sonora and BCS was summarized after an extensive literature review. This information was complemented with current data on the type and size of human population, as well as current development activities, taken from the Instituto Nacional de Estadística, Geografía e Informática (INEGI, www.inegi.gob.mx).

We researched two archives with historical aerial photographs, Ingenieros Civiles Asociados (ICA) and INEGI and scanned 160 photographs from Sonora and BCS taken between 1950 and 1970 with a flat-bed scanner at 600 dpi. Photographs were geometrically corrected and rectified using modern UTM ortho photographs as base maps (http://antares.inegi.gob.mx). Historical photography was then compared with high resolution images from Google Earth and the human development around mangrove ecosystems in both states was visually registered.

Finally, we conducted a series of field visits in Sonora and BCS between 2007 and 2009 in order to assess the intensity of human activities and assess their effects on the mangrove ecosystems and their surrounding environments.

3. RESULTS

3.1. History of development in south-central Sonora

The region that extends from the city of Guaymas to southern Sonora has been occupied by humans since well before the arrival of Europeans. For millennia, native tribes like the Yaqui and the Mayo harvested corn, beans, squash, and cotton and used marine resources (Hrdlicka 1904, González-Bonilla 1941, Doolitle 1984).

In the 16th century, Europeans explored the region by sea and land, searching for gold, pearls and other commodities. However, all attempts to establish settlements failed. In the early 18th century the missionaries started settlements and the first economic activities. With the lethal combination of hard labor and epidemics, they pressured native groups and reduced their population (Treutlein 1939, Almada 2000).

By the end of the independence movement in 1821, local products were being incorporated into the national commerce. The period of President Porfirio Díaz (1883–1911) promoted foreign investments, designed to enhance communication systems and create better public works. This situation attracted migrants from all over the country, accelerating the population growth and the development of economic activities (Coerver 1977). However, during the crisis of 1908 high unemployment forced many to return to the valleys (Almada 2000).

In the 1930s the government promoted a new land distribution scheme based on the ejido, distributed territories to local communities, and fostered the development of agriculture, cattle growth and fishing to promote economic growth. Large investments were directed to construct dams, channels and roads to enhance irrigation-based agriculture and cattle production in the valleys of the Mayo and Yaqui rivers (Almada 2000).

The resources from the ocean were plentiful then, and by the end of WWII the US was again interested in food and raw materials produced in Sonora. The first fishing cooperatives and processing plants were established during this period to capture and process oyster and shrimp, and new investments were directed toward massive production (Almada 2000). The introduction of outboard motors, nylon nets and larger boats in the 1950s accelerated the exploitation of marine resources, which soon started to decimate. Furthermore, the pesticides and fertilizers used in agriculture in the upper valleys were conducted towards lagoons and estuaries by large draining channels, threatening the fishing cooperatives' income (McGoodwin 1980).

Consequently, by the beginning of 1970 soil productivity was severely reduced and fish captures diminished drastically, which resulted in lower revenues and greater debt (Almada 2000). As a strategy to expand the economic alternatives of the ejido sector, aquaculture was introduced in Sonora in 1983. However, limited access to credits and lack of material and technical resources detained rural communities from developing this industry. During the 1990s, new privatization and liberalization policies were created to integrate rural communities into the global economy. However, some of these reforms changed the ejido laws, enabling their members to transfer their lands and encouraging partnerships with the private sector to create credit opportunities (Luers *et al.* 2006). These reforms allowed the private sector to enter the aquaculture industry freely, growing tremendously: in 1993 there were 1000 ha of ponds and between 1994 and 2003 a total of 18,904 ha were constructed, most of these financed by private entrepreneurs. These transformations placed Sonora as one of the fastest growing states; it was a time of productivity growth with cities growing in extent and population, but also a time of severe overexploitation (Luers *et al.* 2006).

3.2. Present state of mangrove ecosystems in south-central Sonora

The first mangrove estuary in southern Sonora is the Yavaros-Moroncarit system, where the town of Yavaros (population 4,000) borders the estuary and the mangroves. Large depositions of trash and other wastes attest to the popularity of these areas as waste disposal sites. In the 1960s a road was constructed to connect Yavaros

FIGURE 5A. Yavaros-Moroncarit System, INEGI 1973, 1:70,000.

with Huatabampo, the largest city in southern Sonora (population 30,000), blocking the natural water flow and caused severe sediment deposition and mangrove mortality. In 1985, because sardine fishing was a profitable activity, industrial and fishing ports, as well as fish processing plants were established in Yavaros (Cisneros-Mata *et al.* 1995).

In recent times the area is undergoing severe environmental problems: sediments and contaminants flush down from the Mayo River valley through large drainage channels, polluting the waters and transforming the estuary by blocking the natural water flows. This situation is aggravated by the direct disposal of liquid and solid wastes from processing plants into the estuary. Finally, the long-term overharvesting of resources has depleted populations of marine species that sustain fisheries (Mora 1997). Figures 5a and 5b illustrate the expansion of agriculture and aquaculture around Yavaros; the channels that direct waste into the estuary are evident.

Estero Tóbari, one of the most productive estuaries in Sonora, is located north of Yavaros. Its mangrove and marine environments are suitable for the reproduction of mollusks, crustaceans and fish, and it creates an important stopover site for migrating species (Balderas *et al.* 1994). The area was severely modified in the 1960s

FIGURE 5B. Yavaros-Moroncarit System, Google Earth.

by the construction of a road to Isla Huivulai which blocked the natural water flows. It also receives pesticides and fertilizers from adjacent agricultural developments through a draining channel, which results in heavy pollution, eutrophication and sedimentation.

South of the city of Guaymas, there is a large system of coastal lagoons that begin in Las Guásimas and end in Estero Lobos. Mangroves are located in the coastal limit of the fertile Yaqui river valley, an area where the Yaqui indigenous nation has exclusive fishing rights. These mangroves are impacted by drainage channels that spill residues into the estuaries, blocking water flows and highly polluting the area causing biodiversity loss. Aquaculture ponds have also been constructed in the area, adding pressure to these coastal environments.

The next mangroves are located around Guaymas and are highly impacted due to the accelerated development of the second largest Mexican port in the Pacific. The economy of Guaymas (population 101,507) started on fishing products and their processing (Almada 2000). The local fishing industry contributed 70% of the state's fishing productivity. However, in recent times the decline of fisheries by overharvesting and the increasing pollution switched economic activities over to assembly

FIGURE 6A. City of Guaymas, ICA 1956, 1:16000.

plants and tourism. Today, Guaymas keeps growing, urban settlements and industrial facilities are being developed all over the bay increasing human pressure on coastal environments, as illustrated on Figures 6a and 6b. There is, however, a growing initiative by environmental NGOs to protect natural ecosystems, and recently the state has declared a large mangrove protected (Estero El Soldado).

3.3. History of development in northern Sonora

For more than 2000 years, the northern part of Sonora was inhabited by semi-nomadic tribes like the Seri, who lived from hunting, fishing and gathering, moving according the availability of resources (González-Bonilla 1941, Almada 2000).

Early European explorations consisted on military reconnaissance missions in the mid 16th century. The first contact with natives occurred in the end of the 17th century, when Jesuit Eusebio Kino established the first settlement in what now is Bahia de Kino. With the foundation of the city of Hermosillo in 1700, the northern territory was consolidated. However, the arid environment and the belligerent nature of the Seri culture slowed the development of the region. Not until the 1970s was the territory of the Seri formerly recognized. At that time, they were granted the exclusive

FIGURE 6B. City of Guaymas, Google Earth.

fishing rights of Canal del Infiernillo, an area with large fishing resources because there are no developments that pollute the marine environment. The Seri created a traditional guard to survey their area for unauthorized fishermen (Wong 1999).

In the early 20th century, a small fishermen settlement existed in Bahia de Kino, which was dedicated to the capture of totoaba (*Totoaba macdonaldii*). Fifteen years later the first fishing cooperative was formed, increasing the population to 500, and the capture of species like sharks and shrimps began (Moreno *et al.* 2005).

From 1965 to 1990 fiber boats, faster motors, nylon nets and diving gears allowed a faster extraction of resources and broaden the fishing area to the west coast of Baja California (Doode 1999). In 1980 a public company created to support the fishing cooperatives at Bahía de Kino, constructed warehouses, and provided work opportunities. The number of fishermen increased as new waves of people migrated to the coast from the adjacent valleys in search of work (Basurto 2006). Soon, the intense harvesting of resources abated natural populations and captures decreased, causing the company to stop operations (Basurto 2006). Conflicts which continue to the present day, started within the community in a struggle for resources between fishermen (Moreno *et al.* 2005).

Aquaculture started as a small experimental and research unit of the Universidad de Sonora in the 1980s. However, several changes in privatization policies during the 1990s promoted its development, and in 2002 thirteen farms produced more than 2500 tons of shrimp exceeding the captures of the fishing industry (Moreno *et al.* 2005).

Fishing opportunities attracted tourism since 1930s, when the first sport fishermen arrived from the US. In 1950 the government promoted tourism in Bahia de Kino by constructing a highway to Hermosillo and expanding electricity and water services, making the city a vacation destination for national and international tourists.

3.4. Present state of mangrove ecosystems in northern Sonora

The first mangroves, going from south to north, are located in Estero Tastiota, where large aquaculture developments have almost removed all mangrove vegetation. Sixty kilometers to the north is the next mangrove community surrounding the Estero Santa Cruz, in the vicinity of Bahía de Kino with a population of 5,000 inhabitants. The structures in the city are mainly constituted by fishermen and tourism houses, restaurants and aquaculture complexes.

Damage to the mangroves comes from trash, construction and liquid wastes disposed directly in the estuary. Aquaculture ponds deposit large quantities of organic matter and sediments that are polluting the waters and blocking their flow. The consequences are noted by the fishermen, whose captures have been reduced by overharvesting and pollution. Figures 7a and 7b show the construction of roads, aquaculture ponds and draining channels connected to the estuary.

The best preserved mangroves in Sonora are located in the land of the Seri, the northernmost limit of their distribution. Human development is scarce, with two Seri settlements: Desemboque and Punta Chueca, with a population of 658 dedicated to fishing and/or crafts. The channel between mainland and Isla Tiburón is known as Canal del Infiernillo and has a series of small mangrove estuaries, the largest being Punta Arenas. Further north is Estero Sargento, with more than 5 kilometers of a large mangrove ecosystem, the last of these ecosystems in the state. Mangrove ecosystems in the land of the Seri are in very good conditions since they acknowledge their importance for the fisheries in their area and therefore protect them. See table 1 for a summarized review of the mangrove localities and the presence of human settlements and/or activities in the state of Sonora.

TABLE 1 (RIGHT). Mangrove localities in the coast of Sonora, Mexico.

Locality	Rhizophora mangle	Laguncularia racemosa	Avicennia germinans	Conocarpus erecta	Fishing intensity	Tourism intensity	% of dead mangroves	Human settlements	Population
Canal del Infiernillo	√	√	√	√	Low	Low	-25%	2 native populations with dirt roads and small houses, hospital and school	674
Estero La Cruz	√	√	√	√	High	High	25%	Large population with all services, paved roads and industries	5,000
Estero El Soldado	√	X	√	√	High	Medium-High	-25%	Port, industries, hotels, restaurants, houses.	97,593 of Guaymas
Manglar de Guaymas	X	√	√	√	High	High	75%	Port, industries, hotels, restaurants, houses.	97,593 of Guaymas
El Rancho	X	√	√	√	High	High	75%	Urban area of Empalme	38,533 of Empalme
Las Guásimas	√	√	√	√	High	Low	25%-50%	Fishermen camps and draining channels	16
Estero Lobos	√	√	√	√	High	Low	25%	Construction in progress	200
Tóbari	√	√	√	√	High	Medium-High	25%-50%	Road dividing the estuary in half, draining channels and aquaculture complex	—
Yávaros-Moroncarit	√	√	√		High	Medium-High	25%	Medium size population, aquaculture, industries	3,860

FIGURE 7A (ABOVE). Bahía de Kino, INEGI 1973, 1:70,000. FIGURE 7B (BELOW). Bahía de Kino, Google Earth.

3.5. History of development in BCS

Researchers estimate that before Europeans arrived, Baja California had a native population of forty to fifty thousand that moved seasonally across the Peninsula hunting, fishing and gathering resources (Del Río and Altable-Fernández 2000).

The first European exploration started in the 1530s, but all attempts to establish a settlement failed because of the extreme arid conditions. It wasn't until the late 17th century that the missionaries established a series of missions starting in the coastal region of Loreto. Missionaries and soldiers gathered the natives and developed a few agriculture and cattle activities, as well as scarce mineral and pearl extraction. After the Jesuits were expelled from all the territories of Spain in 1767, the only activities developed were those necessary to provide the mines with transportation, raw materials and food. The resources needed to sustain these settlements were supplied by mainland Mexico through the port of San José del Cabo (Del Río and Altable-Fernández 2000).

By the beginning of the 19th century, agriculture, cattle and mining activities became more important, and their production reached national and international markets. Trade became a profitable activity and the city of La Paz grew quickly (Del Río and Altable-Fernández 2000).

In the beginning of the 20th century, Porfirio Diaz secured large investments from foreign companies to exploit mineral resources and distributed large portions of land; some of these companies widened their activities to agriculture and cattle growing in order to guarantee local supply. These investments improved the cities, and by 1910 the population grew to 42,000 (Wyllys 1933). The enlargement of human population and economic activities also brought overharvesting of resources and pollution of water bodies by industrial and urban waste (Del Río and Altable-Fernández 2000).

The Mexican revolution started in Mexico in the first decade of 1900, but its effects were hardly felt in the Peninsula. Resources from mainland became scarce, which greatly slowed the local economy, population growth slowed, and by 1929 there was a total population of 47,000 people working in the mining colonies and agriculture/cattle settlements. In response to this lack of expansion, the government promoted surveys between 1930 and 1960 to identify available natural resources. These explorations identified areas suitable for agriculture, but the reports indicated that due to the water scarcity, it could not be practiced intensively. Nevertheless, a series of agriculture policies were created in order to advance the economy, and the government distributed large territories to ejidos and private parties tripling the farming surface (Del Río and Altable-Fernández 2000).

In the 1960s, the southern region of Baja California underwent a large process of industrialization, and credits were granted to farm large surfaces. The ferry to communicate the Peninsula with mainland was introduced, and in the '70s the highway that connected the Peninsula from north to south was finished. This contributed to the development of commerce and tourism, increasing the population to 130,000 inhabitants (Del Río and Altable-Fernández 2000).

Between 1971 and 1980 the federal investment in BCS increased more than 100%. Mining, construction, electricity, communication, transport and fishing industries grew, however commerce and tourism presented the largest growth (Del Río and Altable-Fernández 2000). Hotels, condominiums, restaurants, fishing fleets and other tourism services were intensively developed in La Paz and Los Cabos, and by 1980 the income generated by tourism represented 27% of the total state incomes (Del Río and Altable-Fernández 2000). From 1995 on, the tourism industry has been a major socioeconomic factor in the Peninsula. The construction of large residential and tourism complexes around the Sea of Cortés are increasing water demands, restricting access to resources and polluting surrounding ecosystems with residual waters (Beltrán-Morales 2005, De Sicilia-Muñoz 2000).

Marine resources from the rich waters of Baja California have provided additional sources of profit. In the 1930s fisheries policies were created to support fisheries (Young 2001), and to date 650 species have been identified as exploitable (Cortés-Ortiz *et al.* 2006). On the Pacific coast, species with high commercial value like abalone and lobster represent profitable targets. To this end, large investments have been directed towards new technology and transportation (Chenaut 1985, Vega-Velázquez 2004). The Sea of Cortés coast has less valued species, and most of the fishing here is done by small groups (Young 2001). However, since 1993 the massive-capture fishing activities of less valued species have been largely promoted, contributing to the development of this industry (Felix-Uraga *et al.* 1996). By 2000, BCS ranked fifth among states with plants for transforming fishing products and seventh in the number of cooperatives. To date this industry keeps growing, and in 2002 it contributed more than 12% of the national captures (Cortés-Ortiz *et al.* 2006).

3.6. The Pacific coast

The first mangrove from north to south is located in a 15 kilometers estuary named La Bocana, flanked by two fishing communities of 2,000 inhabitants: Punta Abreojos and La Bocana. The population relies upon lobster and abalone, which are highly valued species in the market and sustain their economy; some others capture clams, oyster and some fish for local consumption (Cortés-Ortiz *et al.* 2006). Southeast from Punta Abreojos is El Coyote estuary (see Figures 8a and 8b), a series of channels and islets covered by mangroves in excellent condition; there is a small lodging

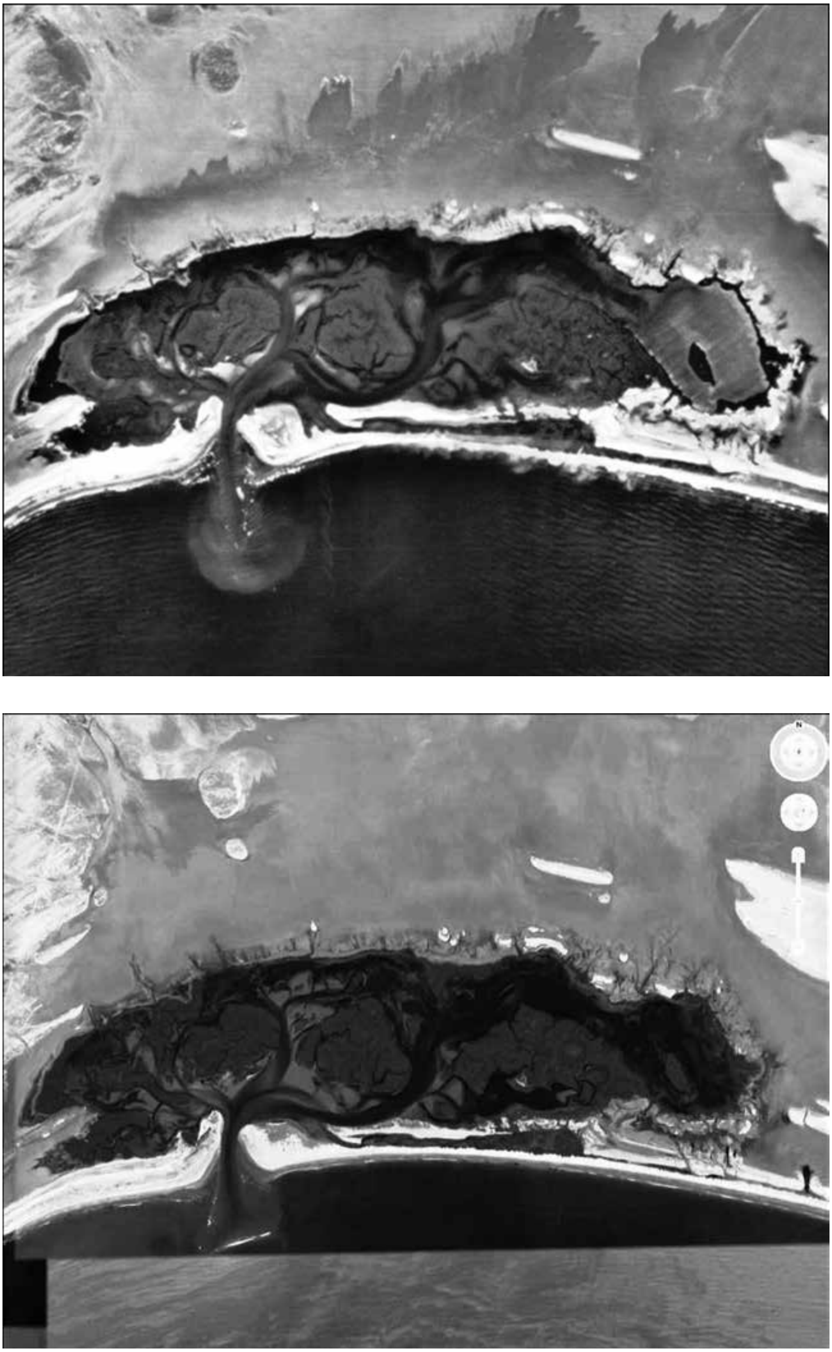


FIGURE 8A (ABOVE). El Coyote estuary, INEGI 1972, 1:70,000. FIGURE 8B (BELOW). El Coyote estuary, Google Earth.

facility with cabins and latrines that was constructed in 1980, as well as a couple of fishermen's houses and oyster farms.

The next mangrove populations are distributed around the Bahía de San Ignacio, an area that was designated as a World Heritage site by UNESCO (INE-SEMARNAP 2000). This ecosystem is in good condition and occupy large areas around Estero El Cardón, which continues south to Estero El Dátil; the population is distributed in three settlements: Luis Echeverría and El Cardón with 1,000 inhabitants, and El Dátil, which is located adjacent to the estuary of the same name with less than 100 inhabitants. Fishing is the principal activity of the local population, however there is a growing number of people working in oyster farms.

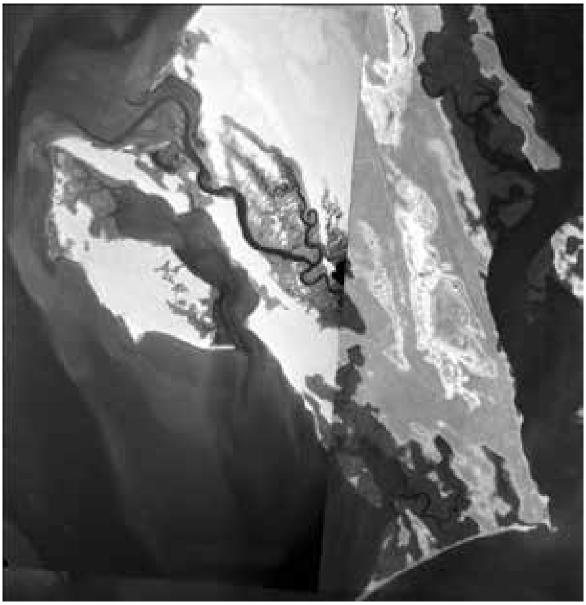
Further south, the area of Bahía Magdalena-Bahía Almejas, is the largest mangrove ecosystems of BCS distributed in a complex set of estuaries and channels covering more than 130 kilometers. This region is one of the most important coastal zones in northwest Mexico and contributes with 65% of the BCS fishery production (Lluch-Belda *et al.* 2000). Human population is distributed mainly in two port cities: Puerto Adolfo López Mateos and Puerto San Carlos, the rest lives in small fishermen camps scattered along the coast.

Puerto Adolfo López Mateos is a town of 2,200 inhabitants, who live mainly from fishing or working in cannery industries, plus whale watching services. A smaller portion works in commerce, education and health centers (Tovar-Vázquez 1997, Gardner and Chávez-Rosales 2000). Mangrove ecosystems are all over the channel and estuaries and are, in general, in a healthy condition, though in the vicinity of a cannery many dead mangroves were evident, probably due to the residual waters that are discharged at very high temperatures.

The port of Puerto San Carlos, 45 km. to the south, has a large drought that serves the fishing industry, supplies tourist ships, and transport goods from agriculture developments (Tovar-Vázquez 1997). The town has 3,600 inhabitants which work in fishing, agriculture, and tourism, as well as in industries like canneries and thermoelectric plants.

Dead mangroves were observed close to these cannery industries probably due to the discharges; furthermore, in some areas where mangroves are adjacent to the city, the accumulation of construction debris and household trash block the natural water flux and killed mangroves. Figures 9a and 9b show how in Puerto San Carlos, the most evident changes were due to the growth of the city, the expansion of roads and bridges and the development of the port.

Mangroves continue south of Puerto San Carlos to the bays of Almejas and Santa María. The population in this area is distributed mainly in Puerto Chale with a



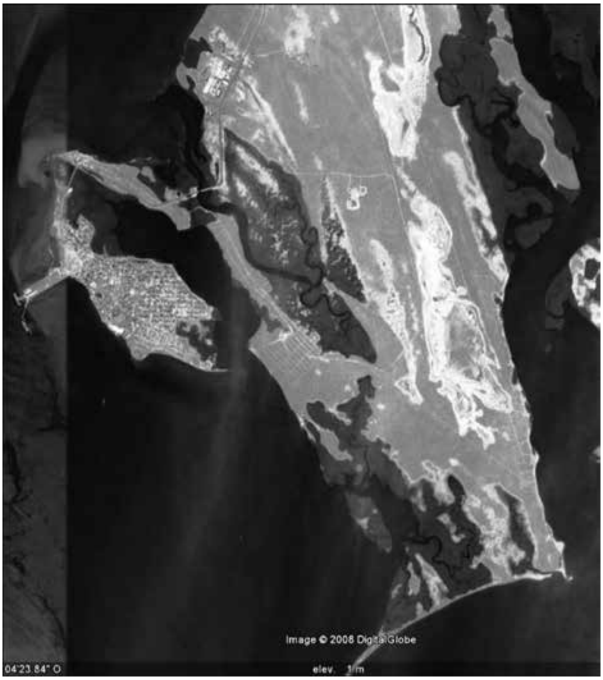


FIGURE 9A (ABOVE). Puerto San Carlos, ICA 1962, no scale available. FIGURE 9B (BELOW). Puerto San Carlos, Google Earth.

population of 300 highly marginalized inhabitants that harvest crabs, scallops and fish. In the shrimp and clam seasons more fishermen arrive to this area, reaching a population of 1,200 temporary residents (Tovar-Vázquez 1997). Formerly there existed a large sea farming complex owned by an ejido; however, it was recently sold to foreigners to develop tourism facilities; presently two private shrimp farms were also established. Rancho Bueno is the last estuary with mangroves in BCS, there is only one settlement running a small oyster farm that has been in operation for 10 years, and the mangroves there are in good condition.

3.7. Present state of mangrove ecosystems of Baja California Sur—The coast of the Sea of Cortés

Mangroves in this coast are distributed on different coves and inlets in small to medium size patches. Bahía Balandra is the southernmost mangrove on this coast, where a coastal lagoon is surrounded by mangroves in good condition, since this bay, near the city of La Paz, has recently been declared a protected area. Further north is another estuary called El Merito that is still in good condition, however, the access has been closed by a private owner and the area is soon to be developed for tourism. Bahía Pichilingue is an area with high tourism and industrial developments, constructions include a shuttle port, fuel and cement factories, universities and tourism facilities. Embedded in the city of La Paz is a small coastal lagoon called Enfermería, which has been severely polluted and damaged by road construction and aquaculture development.

Other mangroves are embedded in La Paz, a city of 189,176 inhabitants who live mainly from tourism. The city has a large port and airport, as well as several industries and tourism facilities that contribute important profits to the city. Due to its arid location, water scarcity is a problem, and with more hotels under construction water supplies and environmental quality are being compromised. These mangroves show disturbance signs like oil, trash and construction debris deposition. In front of Bahía de La Paz is a large mudflat called El Mogote, with some mangrove populations facing the bay, the area is undergoing rapid tourism developments that represent a threat to the conservation of these ecosystems (Holguin *et al.* 2006). Figures 10a and 10b show the growth of La Paz, with a notable urban and industrial expansion, as well as the construction of roads around the bay and on El Mogote.

North of La Paz is the Espíritu Santo Island, which was declared a protected area in 2001. The west side of the island has eight mangrove sites in excellent condition. In 1903, some facilities were built for the production of pearls and opening channels through the mangroves. However, the facility was abandoned in the '70s due to production failure. Presently there are no settlements in the island and the impact of tourism is very low.

FIGURE 10A (ABOVE). La Paz, ICA 1956, 1:20,000. FIGURE 10B (BELOW). La Paz, Google Earth.

Some small mangrove patches are located along the coast to the north up to Loreto. The first is located in Puerto Escondido, a marina that projects to have hotels, condominiums, golf courts, ferry areas and a commercial port (De Sicilia 2000). Some mangroves were removed during the construction of the port, but a few patches are still left. However, the environmental conditions in the area will soon be modified by the projected development that has already changed the morphology of the port.

A couple of kilometers north, in the Loreto-Nopoló area, another series of mangroves located in the vicinity of Ligüi were severely damaged during the 2003 hurricane season. Some other small mangrove stands are around the community of Ensenada Blanca, where a hotel is being developed and conflicts with fishermen are already occurring by restricting their access to the beach. A couple of miles north from Ensenada Blanca, a medium size mangrove estuary was completely covered with sand in 1976–1977 by the National Fund for Tourism Encouragement to develop the Loreto-Nopoló-Puerto Escondido corridor.

The next mangrove population to the north is located in a series of coves along the west coast of Bahia Concepción. The first is Ensenada El Manglito, a large mangrove stand in good condition and with a small fishing community, followed by Playa Armenta, a small mangrove area next to a hotel and an RV camp. These populations are in poor condition, since construction and debris have blocked and changed the water flow. Santa Barbara has two patches of mangroves with no signs of human presence; however, an ongoing large project is expected to construct golf courses, marinas, hotels and houses. El Burro, has a medium-sized mangrove patch bordering a lagoon, and small houses distributed along the shore, the lagoon is being filled in by local inhabitants to reduce its surface and eventually kill the mangroves, which represents nuisance vegetation to them. The last mangrove area is the largest population and is located in Playa Santispac, where little tourism development is still present.

Continuing to the north is the town of Mulegé, located next to a large estuary that flows into the Sea of Cortés with a population of 3,317 inhabitants. Mangroves in the inner part of this estuary show disturbance by urban development and road construction, which have partially blocked it with rocks and other debris. Fishermen concentrate their activities in the sea and almost no fishing is practiced in the estuary. Figures 11a and 11b show the construction of roads, urban and tourism developments in Mulegé. Another impact to mangroves in the area is the occurrence of hurricanes, which periodically damage this vegetation.

The last mangrove stand along this shore in BCS is located 50 kilometers north of Mulegé in a small settlement called San Lucas, which has tourist houses, RVs and

FIGURE 11A (ABOVE). Mulegé, ICA 1956, no scale available. FIGURE 11B (BELOW). Mulegé, Google Earth.

military barracks. A thin bar of sand forms a small inlet, where mangroves are in well conserved patches. Among the population of 203 inhabitants fishermen capture squid and fish from the sea, and clams, crabs, oyster and octopus in the mangroves. See tables 2 and 3 for a summarized review of the mangrove localities and the presence of human settlements and/or activities in the Peninsula of Baja California.

4. DISCUSSION

In the last century, the landscape of northwestern Mexico changed gradually along with the intensification of economic alternatives; and today changes keep occurring at accelerating rates. Many of these transformations have affected the environmental conditions of coastal ecosystems, diminishing their capacity to provide valuable ecosystem services, as well as having detrimental effects on the flora and fauna associated with mangroves Enríquez-Andrade *et al.* 2005, Whitmore *et al.* 2005).

In the arid northwestern regions of Mexico, damages can be identified following the historical development of human populations. The degree of human damage to mangrove ecosystems varies depending on the type, frequency, and intensity of the development activities (Adeel *et al.* 2002, Duke *et al.* 2007).

In the central-southern region of Sonora, humans have been present for a longer time, and the mangrove ecosystems show evident signs of deterioration. Agriculture and cattle practices in the upper valleys dispose of large quantities of chemicals and fertilizers through draining channels where they merge with municipal wastewaters and are finally emitted as coastal discharges. All are conducted to coastal and estuarine areas by large draining channels, resulting in sediment accumulation and severe environmental pollution. Resource overharvesting has decimated the populations of valuable plant and animal species, having deleterious impacts on local and regional fisheries, which is causing poverty and resource over extraction.

Some mangrove populations have been almost completely removed for the construction of aquaculture complexes, as well as by the direct disposal of their solid and liquid wastes, and some are so severely damaged that their recovery seems very difficult if not impossible. For these reasons, it is imperative that the construction of these complexes is properly planned and evaluated in order to reduce environmental impacts (Whitmore *et al.* 2005).

Other estuaries that have a more recent history of development and in these places the vegetation is in apparent good condition. However, since mangrove species have proved to be very tolerant to disturbance (Alongi 2008), it is in these estuaries that water quality assessments are crucial to adequately verify that the discharges'

TABLE 2. Mangrove localities in the Pacific coast of BCS.

Locality	Rhizophora mangle	Laguncularia racemosa	Avicennia germinans	Fishing intensity	Tourism intensity	% of dead mangroves	Human settlements	Population
La Bocana	√	√	X	Medium-High	Low	-25%	Houses, industries, small ports, fishing camps	2,000
El Coyote	√	√	X	Medium	Medium	-25%	Houses, hotels and restaurants	15
Bahía San Ignacio	√	√	X	Medium	Medium-High	-25%	Tourism camps ejidos Luís Echeverría and El Cardón	1,000
El Dátil	√	√	X	Low	Low-Medium	25%	Ejido El Dátil	-100
Puerto López Mateos	√	√	√	Medium	Low-Medium	50%	City with port and industries	2,200
Puerto San Carlos	√	√	√	High	Medium-High	20%	City with port and industries	3,600
Puerto Chale	√	√	√	Medium	Low	-25%	Fishing camps	300
Loma Amarilla	√	√	√	Low-Medium	Low	25%-50%	Aquaculture ponds	0
Rancho Bueno	√	√	√	Medium	Low	-25%	Fishing camps and oyster farms	8

TABLE 3. Mangrove localities in the Sea of Cortés coast of BCS.

Locality	Rhizophora mangle	Laguncularia racemosa	Avicennia germinans	Fishing intensity	Tourism intensity	% of dead mangroves	Human settlements	Population
Bahía Balandra	√	√	√	Medium-High	Medium	-25%	—	—
Bahía El Merito	√	√	√	Medium-High	Medium	-25%	—	—
Bahía Pichilingue	√	X	√	Medium-High	Medium	50%-75%	Port, industries, hotels, restaurants, houses.	200,000 of La Paz
Puntas Prieta and Colorada	√	√	√	Medium-High	Medium	50%-75%	Aquaculture complex, houses, restaurants and industries	200,000 of La Paz
El Zacatal	X	X	√	Medium-High	Low	75%	Urban area of La Paz	200,000 of La Paz
El Comitán	X	√	√	Medium	Medium	25%-50%	20 houses	100
El Mogote	√	√	√	Medium-High	Medium	25%	Construction in progress	—
Isla Espíritu Santo	√	√	√	Low	Medium-High	-25%	—	—
San Evaristo	X	√	X	Medium	Low	75%	Fishermen population	60
Isla San José	√	√	√	Medium-High	Low	-25%	—	—

TABLE 3 (CONTINUED). Mangrove localities in the Sea of Cortés coast of BCS.

Locality	Rhizophora mangle	Laguncularia racemosa	Avicennia germinans	Fishing intensity	Tourism intensity	% of dead mangroves	Human settlements	Population
Timbabichi	√	√	√	Medium-High	Low	-25%	Fishermen population	60
Agua Verde	X	√	X	Medium-High	Low	-	Fishermen population	172
San Cosme	X	√	√	Medium-High	Low-Medium	25%	Fishermen population and luxury hotel	20
Ligüi	X	√	X	Low-Medium	Low-Medium	75%	Fishermen population	200
Puerto Escondido	√	X	X	Medium-High	Medium-High	-25%	Port facility	—
Ensenada El Manglito	√	√	√	Low-Medium	Low-Medium	-25%	Fishermen camps	—
Puerto Escondido	√	X	X	Medium-High	Medium-High	-25%	Port facility	—
Ensenada El Manglito	√	√	√	Low-Medium	Low-Medium	-25%	Fishermen camps	—
Playa Armenta	√	√	√	Low-Medium	Low-Medium	-25%	Dirt road	—
Playa El Requesón	√	√	√	Low-Medium	Low-Medium	-25%	Palapas and latrines	—

TABLE 3 (CONTINUED). Mangrove localities in the Sea of Cortés coast of BCS.

Locality	Rhizophora mangle	Laguncularia racemosa	Avicennia germinans	Fishing intensity	Tourism intensity	% of dead mangroves	Human settlements	Population
Playa San Buenaventura	X	√	√	Low-Medium	Medium	25%	Small houses, stores, hotel and restaurant	—
Santa Bárbara	√	√	√	Low-Medium	Low-Medium	-25%	Construction of tourism development	—
Playa El burro	X	√	√	Low-Medium	Medium	25%	Houses on the beach and road over mangrove	—
Playa Santispac	√	X	√	Low-Medium	Low-Medium	—	—	—
Mulegé	√	√	√	Medium-High	Medium-High	25%-50%	City	53,000
San Lucas	√	√	√	Medium	Low-Medium	-25%	Houses, tourism and fishermen village, military headquarters	203
El Rincón	X	√	√	Low-Medium	Medium-High	-25%	Dirt road	—
La Mona	X	√	X	Low-Medium	Medium-High	-25%	Small houses own by tourism	8

concentrations and the input of water do not harm the estuarine environmental conditions (Paez-Osuna *et al.* 2003).

The northern region of Sonora constitutes a different scenario because the area is scarcely populated and human activities have been practiced for a shorter period of time. Estuaries in Seri territory are in excellent conditions because development is scarce and the Seri survey their lands for unauthorized resource poaching. The mangroves along Canal del Infiernillo are particularly well protected, by both the traditional and the environmental authorities. Efforts and resources are being directed to decree this area protected an endeavor that will not only ensure the conservation of mangroves, but of other coastal ecosystems and will allow the continued provision of environmental services that benefit local communities.

Finally in Bahía de Kino, recently developed unplanned activities have caused serious environmental damages. Urgent restoration measures are needed to protect the resources left, to eventually restore natural conditions, and perhaps recover ecosystem services that have been lost, such as the maintenance of fisheries.

Human development in BCS has a more recent origin and the environment has not been as damaged. Nonetheless, recent accelerated population growth and increasing human activities are exerting pressures that are endangering the peninsular environment. The Sea of Cortés coast in this state has experienced drastic modifications for the last 50 years as a result of the construction of tourism and industrial facilities (Enríquez-Andrade *et al.* 2005). Several mangrove populations along this coast are still in good condition, like those in Bahía Concepción; however, there are many tourism developments planned or already underway which will seriously threaten these ecosystems in the future, as has already happened in Sonora and in other regions of BCS like Mulegé or Loreto.

Along the Pacific coast of BCS, development has not yet been very intense, perhaps because the area is not as attractive for tourism and/or because the roads are scarce. Mangrove ecosystems in this coast are the largest in the state, and even though the northern limit of their distribution (Bahía de San Ignacio) is protected by UNESCO, the largest surface in the state represented by those of the Bahía Magdalena-Bahía de Almejas complex, is still without protection. Therefore, we consider that this area should be a priority for authorities, because it provides many goods and services from which both society and nature benefit. There are few aquaculture developments in the area and their activities can still be regulated before the environment quality is compromised, however, our main concern is the large investments already underway to develop tourism facilities, which will impose pressure on water demands and the biodiversity, as has already happened in other places. If such accelerated and unplanned growth is to continue, the scenario will be similar to that of the opposite coast or in Sonora, where pollution and scarcity of resources are the prevailing conditions of this once fisheries rich coast.

The landscape we see today can only be understood if we are acquainted with its history (Swetnam *et al.* 1999), therefore our main interest is to provide lessons of how hastened and unplanned decisions have caused the uncontrolled development of economic activities in the area in order to generate short term profits. The intensity of these activities may reduce the possibilities to practice others by the pollution of the soil, the depletion of water and reduction of biodiversity; and in the long term, these may have consequences that will even impede the development of the original activity itself.

The analysis of historical aerial photography used in this study was useful to illustrate the accelerated claiming of natural environments by humans, because they are often the only available source of information from times when ecosystems were less affected by humans. The review of historical and socio economic information complemented this visual analysis by informing about the relationship between population and the natural environments, since ecological changes are closely connected with socio economic factors like management regimes and the intensity of practices that have affected and changed the landscape throughout history.

It is hard to say if the increasing rate of conservation efforts will be able to stop the accelerated environmental degradation in northwestern Mexico, however there is a growing awareness of the importance to protect the natural environments around the Sea of Cortés, particularly mangrove ecosystems, which are vital for many biological processes and for the survival and well being of biodiversity and mankind.

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FISHERIES OF NORTHWEST MEXICO

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The northwest region of Mexico supplies the most abundant share of fish products in the country. Most of the region is a temperate-tropical transitional area. Coastal wind-induced upwelling occurs seasonally along the west coasts of both the Baja California Peninsula and the continent. Permanent topographical upwelling takes place in two large areas. Fisheries are mostly industrial, Sonora being the largest producer in Mexico, followed in the region by Sinaloa, Baja California Sur and Baja California. The most abundant fishery is that of small pelagic fishes, while the jumbo squid fishery follows some years. The most valuable fishery in the country is that of the penaeid shrimp in the Gulf, together with a rapidly expanding aquacultural component. Abalone and lobster fisheries are the main economic activity for some 10,000 inhabitants in 30 settlements at the west coast of the Peninsula. Other small scale fisheries include blue crabs, sea snails, clams and the large number of scale fish and sharks, skates and rays fisheries. These create the largest number of jobs and produce the most of fresh fish products for the local and regional markets. It has been claimed that coastal food webs have been "fished down" in the Gulf; however, other studies based on widely accepted methodology have shown opposite results, concluding that there is no sign of fishing down.

1. PHYSICAL SETTINGS

The northwest region of Mexico supplies the most abundant share of fish products in the country. Most of the region is a transitional area, the eastern boundary of the North Pacific Gyre (Lynn and Simpson 1987) where the temperate California Current mixes with tropical ones resulting in a wide, productive area (Badan-Dangon 1998). Coastal wind-induced enriching upwelling occurs seasonally along the west coasts of both the Baja California Peninsula and the continental Sonora and Sinaloa states. At the west coast, atmospheric forcing is strongly seasonal; the California Current (CC) does reach the tip of the Peninsula and the mouth of the Gulf of California; modified water of the CC is recognizable in the vicinity of the Revillagigedo Islands (Lluch-Cota *et al.* 1994) about 19°N, particularly from February to June when SSTs are lower, upwelling is maximum and the current intensifies.

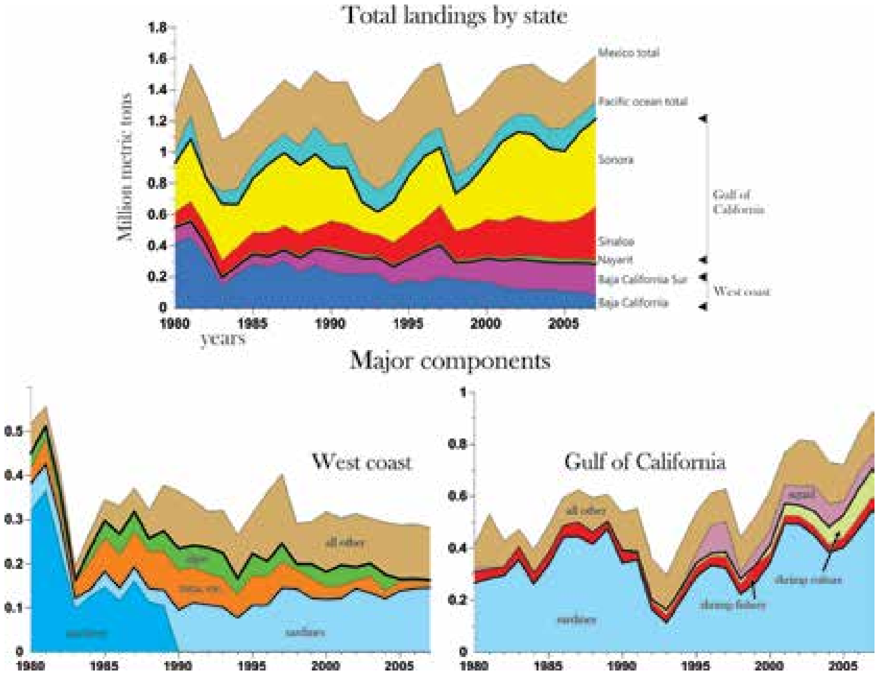
Inside the Gulf, weak southeasterly winds blow through the summer and stronger northwesterly ones during winter, mostly polarized along the Gulf axis (Merrifield and Winant 1989, Marinone *et al.* 2004). Rainfall takes place mostly during the summer (Salinas-Zavala *et al.* 1998), together with the northwestward transport of large amounts of water vapor (Carleton *et al.* 1990). The Gulf of California is a Class I, highly productive ecosystem (> 300 gC/m2-yr) based on global SeaWiFS primary productivity estimates, one of the five marine ecosystems with highest productivity and biodiversity (Enríquez-Andrade *et al.* 2005). The northern Gulf has two main natural fertilization mechanisms: year-round tidal mixing around the large islands leading to an area of strong vertical mixing and continuous flow of cool nutrient-rich water into the euphotic layer, and a thermal refuge for temperate species during the warm part of the year or along warm interannual events (Lluch-Belda *et al.* 2003); the second, wind-induced upwelling along the eastern central Gulf, enriched waters from the islands and the east coast reaching the peninsular side and remaining trapped contributing to higher primary production per unit area. Also, because this enrichment system operates only during winter, there is a strong annual gradient of pigment concentration in most of the Gulf (Lluch-Cota *et al.* 2004).

Permanent topographical upwelling resulting in high productivity year-round takes place in two large zones, Punta Eugenia-Sebastián Vizcaíno at the west coast and around the large islands in the Gulf (Lluch-Belda *et al.* 2003).

2. FISHING ACTIVITIES

Accordingly, temperate affinity species as small pelagic fishes, spiny red lobster, abalone and giant kelp are abundant at the cooler west coast of the peninsula; at the large islands area within the Gulf small pelagic fishes conform the bulk of the landings, while tropical kinship ones as penaeid shrimp, giant squid, tuna and billfishes are to be found in warmer waters in the Gulf and the south west coast of the Peninsula (see Figure 1).

The region has over 60% of the shrimp trawlers in the country; 73% of the tuna boats; all the sardine boats; 20% of the scale fishing boats and 28% of pangas (small boats powered by outboard engines). Clearly, industrial fisheries dominate the stage (see Figure 2).



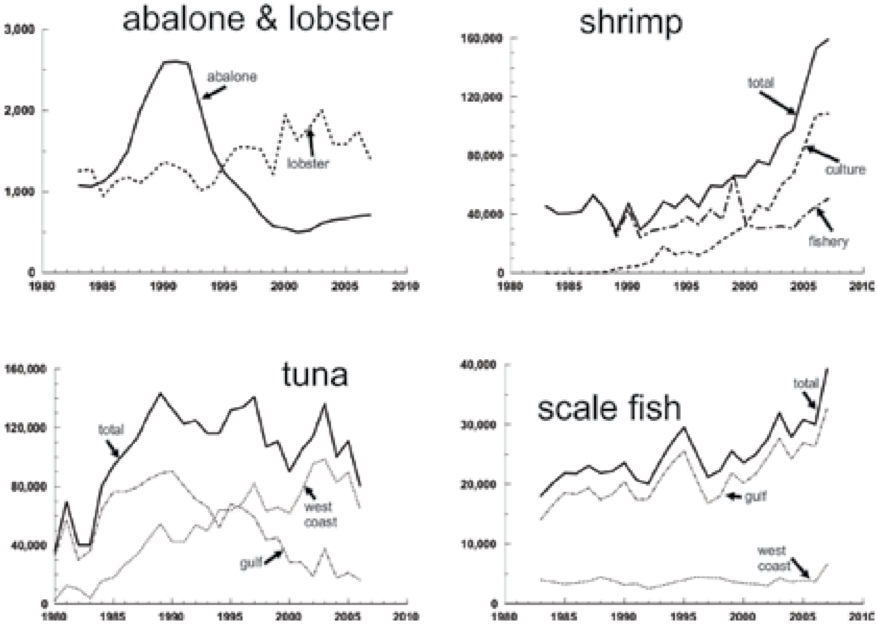


FIGURE 1 (ABOVE). Catch trends of the main fisheries at the Baja California Peninsula and Gulf of California, by state and coast. FIGURE 2 (BELOW). Catch trends of some of the main fisheries at the northern Pacific of Mexico.

There is a register of 74,639 persons involved in fishing activities in northwest Mexico, of which 46% are in Sinaloa, 28% in Sonora, 14% in Baja California Sur and 11% in Baja California; estimates do not differ significantly from 1997 to 2002.

The west coast of the Baja California Peninsula includes landings from both Baja California and Baja California Sur states; the share of the first one was maximum around 1981, mostly driven by the anchovy fishery, which vanished in 1990. Since then, landings at that state have been slowly declining, sardines remaining as the main volume contributors. Tuna and other large pelagic are also considerable, and tuna ranching has become an important activity. Algae, mostly *Macrocystis* whose volumes have been important have declined in recent years, mostly after the closure of the 'Productos del Pacífico' plant in 2004, which landed some 3,000 t (metric tons)/year. A new company (Albiomar) has begun operations, about 3,000 t/year. Landings of another species, *Gelidium*, have continued normally.

Within the Gulf, Sonora is by far the largest producer in Mexico, landings of the country fluctuating at its pace. By far the most abundant fishery is that of small pelagic fishes, mainly sardines, that has recently reached over 500,000 t. In terms of volume, the recently developed giant squid fishery (*Dosidicus gigas*) follows some years, although landings are extremely variable. The most valuable fishery in the country is that of the penaeid shrimp in the Gulf, together with a rapidly expanding aquacultural component whose production has already surpassed the wild capture fishery.

Many species comprise the rest of the landings, including scale fishes; sharks, skates and rays; a number of mollusks including the highly valuable abalone at the west coast, several clams and oysters; crustaceans other than shrimp, including the also highly prized spiny lobster fisheries and sizeable amount of blue crabs; other invertebrates as sea cucumbers and sea urchins and, recently, a medusae fishery in development.

3. THE ABALONE AND LOBSTER FISHERIES

Both fisheries have been the basis for the development of about 30 settlements at the west coast of the Peninsula; the main economic activity for some 10,000 today inhabitants. Both fisheries were a concession to fishery cooperatives with exclusive fishing rights until the mid 1970s. Area concessions have been in effect since then.

The abalone fishery began during the mid 19th century by Chinese and later Japanese fishermen. Since 1940 it has been undertaken by Mexican fishermen. Regulations of the fishery began quite soon; minimum size limits were established in 1926, based on those in effect in California; a closed season was decreed in 1956 (January to March) and was changed for July to August in 1972, based on spawning activity. Also in 1956 new larger size limits were imposed, that were raised again in 1981. In spite of such measures, landings declined since the early 1970s with no recovery of previous levels until now.

During the high landings period the main species was the pink abalone (*Haliotis corrugata*), while the green abalone (*H. fulgens*) has dominated since the 1970s, declining after 1990 (see Figure 2).

Today, the fishery develops within the frame of a comprehensive management system, involving yearly biomass estimated for each field, catch quotas stemming from such estimates and explicit considerations on the effects of environmental variability.

As a result of this system, and of favorable environmental conditions, the fishery is in a process of slow, but consistent recovery from its historical minimum.

The west coast of the Peninsula is the major production area for lobster; three species are harvested: *Panulirus interruptus* (California spiny lobster), *Panulirus inflatus* (Blue spiny lobster) and *Panulirus gracilis* (Green spiny lobster); the first one comprises 95–97% of the total landings. The fishery is under the concession of 26 cooperatives (5 in the northern area, 10 at the central and 11 at the southern ones), (Vega-Velázquez *et al.* 1996).

Minimum cephalotorax size of 82.5 mm and closed seasons per area are the main regulations in the fishery. Cooperatives may operate with different levels of organization, from those with little control and no processing plants to those fully integrated, with reception and processing plants. Most production is exported as cooked tails and live to markets to orient and a small portion to Europe.

The fishery has a history spanning more than 100 years, one of the oldest and best organized in Mexico (Vega-Velázquez and Lluch-Cota 1992, Vega-Velázquez *et al.* 1996, Vega-Velázquez *et al.* 1997). It was underexploited up to 1940, after which it increased to more than 1,000 t/year until the mid 1970s; since then it has been mostly leveled off at about 1,500 t/year (see Figure 2).

The fishery in the central area (Punta Abreojos to Isla Cedros) was certified for sustainability by the Marine Stewardship Council in 2005 and recertified during 2011, including the small fishery at Isla de Guadalupe. This is the first fishery that has passed the MSC certification process twice in Latin America.

4. SMALL PELAGIC FISHES

Fishing for small pelagic fishes in Mexico started off Ensenada, Baja California, as an extension of the California sardine fishery in the late 1920s. During a couple of decades catches oscillated between 1,000 and 12,000 t/year, until the collapse of the

California Current System sardine, in the early 1950s (Radovich 1982). After the collapse, the fishing industry moved southward looking for new fishing grounds, establishing a small scale fishery off Isla Cedros in the early 1960s, inside Magdalena Bay in the late 1960s (Felix-Uraga 2006) and later, during the early 1970s, all the way around the Peninsula to the central Gulf of California (Cisneros-Mata *et al.* 1996).

In the early 1970s, fishing for northern anchovy increased in Ensenada as a response to the Peruvian anchovy collapse, opening new markets for the reduction industry (Lluch-Cota *et al.* 2006). This fishery grew to over 260,000t/year in 1981, decreasing rapidly afterwards to only 4 t in 1998; this collapse resulted in closure of virtually the entire industrial infrastructure in that port.

Isla Cedros reported catches for only a few years, and today is considered as an important potential fishing ground after several direct and indirect biomass estimates during the last decades. Inside Magdalena Bay the fishery has remained nearly stable, with annual average catches of 10,000 t for the 1972 to 1993 period, and up to 35,000 t/y for the 1994 to 2006 period.

Inside the Gulf, the Pacific sardine fishery became the most abundant in the country, contributing with up to 40% of total national marine catch in some years. The Pacific sardine is the dominant (50–80% of total landings) in a multispecies purse seine fishery that operates from ports in the central and southern Gulf of California, from November through July (Nevarez-Martínez *et al.* 1999). Sardines and other small pelagic fishes are also caught in relatively small numbers near the mouth of the Gulf for use as bait by vessels targeting tuna (Rodríguez-Sánchez *et al.* 2002). After being established in the early 1970s, landings peaked in 1988–1989 at nearly 300,000 t. After that, in the early 1990s, a dramatic collapse occurred to less than 3% in two years, resulting in the loss of around 3,000 jobs, and about half of the fleet and processing plants (Lluch-Cota *et al.* 1999). After that, the fishery rapidly recovered to around 200,000 t and showed alternating high and low catch periods of 3 seasons each, until the most recent season, 2008-2009, that reached an unprecedented peak of almost half a million t. The other component of the northwest Mexico small pelagic fishery occurs off Mazatlán, in the southernmost part of the Gulf of California, based on less than 10 boats and catching mostly tropical species, with nearly stable catch levels.

By early 2009 the fleet was composed of 96 boats, more than half of them operating in the central Gulf. About 85% of the total catch is used for reduction to fishmeal, mostly for animal feeds. Sardines are also packed in cans for sale to domestic and foreign markets, and recently a new market opened due to the development of tuna ranching demanding live or frozen sardine. This market is attended by the Ensenada fishery. One interesting aspect is that during years of poor sardine abundance, low catches are compensated to some degree by increases of other small pelagic fishes such as the tropical thread herring *Opisthonema* spp. (Lluch-Belda *et al.* 1986) and, starting in the early 1990s, the tropical anchovy *Cetengraulis mysticetus*. For this reason, the reduction industry is not as strongly affected by low abundance periods as the canning industry, in which there has historically been a clear preference for sardines (Lluch-Cota *et al.* 2007).

Regulation is based on the Norma Oficial Mexicana (NOM) 003-PESC-1993, which recognizes that the abundance of sardine and other small pelagic species fluctuates with environmental conditions but can also be influenced by fishing. The NOM specifies a minimum size limit of 150 mm in length for sardines, regulates fishing gear and fleet capacity, and requires that the fishery be closed in times and areas where the majority of sardines are spawning. The fishery does not yet have a formal fishery management plan, although one was proposed by Nevarez-Martínez *et al.* (2003) and is presently being completed. Since 1993, the Centro Regional de Investigación Pesquera in Sonora, a branch of the Instituto Nacional de Pesca (INAPESCA), has conducted a pre-season exploratory fishing survey in the fishing grounds, in cooperation with the fishing industry, in order to forecast expected catches for the year. If the abundance of fish on the grounds is low, the INAPESCA and the industry can agree to more extensive time and area closures.

Recently, the interest for adoption of ecosystem based management (EBM) is growing among scientists and resource administrators. Bakun *et al.* (2009) discussed some of the characteristics of small pelagic fisheries that should be taken into consideration to develop EBM. These include evaluating the openness of the system (interaction with wider oceanographic conditions in the surrounding coasts) and the large moving capabilities of these animals, the inclusion of the large abundance fluctuations exhibited by these species instead of the traditional conception of equilibrium conditions, and the understanding of their real trophic role in the ecosystems. The Gulf of California sardine fishery was certified for sustainability by the Marine Stewardship Council (MSC) in 2011. This is the first fishery targeting small pelagic fishes and using the catch mostly for industrial purposes (reduction to fishmeal and oil) to be certified under MSC standards in the world.

The large fluctuations registered for the two largest fisheries, the anchovy off Ensenada and the Pacific sardine inside the Gulf, are similar in intensity to those of other areas of the world, and it is likely that they covariate with other fisheries in the 40–60 year band frequency (*i.e.* The regime frequency, Lluch-Belda *et al.* 1992); however, Ensenada trends are confusing since large portion of the industry disappeared in the 1990s, and in the Gulf there seems to be strong variability at a higher frequency that might confound the regime signal. Bakun *et al.* (2009) noted that contrary to what happens in the California Current system, the Gulf represents the tropical (warmer) distribution limit of the northeast Pacific sardine (Lluch-Cota 2000); while warm periods appear to be beneficial for the California Current sardine (Lluch-Belda *et al.* 1989, 1992), its has been observed that high temperatures associated with ENSO diminish or even suspend the annual southward migration of the sardine within the Gulf, thus reducing catches (Lluch-Belda *et al.* 1986, Huato-Soberanis and Lluch-Belda 1987) and affecting reproduction (Lluch-Cota 2000).

One interesting, still unsolved, issue relevant for management is whether the Gulf of California sardine should be considered a separate stock from that of the western Baja California Peninsula. Even though California sardines are harvested in the Gulf, they have been considered implicitly separated by assumed isolation from the west coast populations (Schwartzlose *et al.* 1999). The same is true for mackerel (*Scomber japonicus*) and northern anchovy (*Engraulis mordax*) population, among others. However, recent investigations indicate substantial interchange of both water masses and organisms between the west coast of the Peninsula and the Gulf of California (Lluch-Belda *et al.* 2003).

5. THE JUMBO SQUID FISHERY

The jumbo squid is an endemic species of the Eastern Pacific Ocean, distributed from California (approx 40°N) to the south of Chile (45°S) (Nigmatullin *et al.* 2001). During recent years a significant northward expansion of its area of distribution has been observed, with frequent records in the states of Oregon and Washington (USA), and more sporadic in British Columbia (Canada), reaching Alaska (Cosgrove 2005, Gilly 2005, Wing 2006, Zeidberg and Robison 2007), as also occurred during the 1930s and 1940s (Levy 2007). This expansion is evident at the west coast of the Baja California Peninsula, mainly around the Biological Action Centers (Lluch-Belda 2000), meaning a potential fishing for Mexico. The fishery has become one of the most relevant ones at the region. It began around the early 1970s by small pangas; in 1980 permits were granted to large boats and landings reached 22,000 t, but the fishery collapsed during 1982 and no squid was available for almost a decade. The decline has been blamed on overexploitation and market conditions by different authors.

Squid reappeared in 1989 and by 1994 the fishery was operating at the central region of the Gulf with a seasonal pattern that is consistent up to date: during the summer months it is undertaken around Santa Rosalía (Baja California Sur) by pangas, while the catches during the winter months are located around Guaymas (Sonora), mostly by shrimp trawlers working together with pangas (Markaida and Sosa-Nishizaki 2001). Recently, catches at the west coast of the Peninsula have been more frequent, mainly during strong ENSO events; the last two years the Mexican Government released some permits to catch jumbo squid in Ensenada, B.C. Additionally, a small fleet of shrimp-modified-boats from Mazatlán, Sinaloa, is fishing between Mulegé and Loreto along the Peninsula east coast. They operate with squid-machines provided with small jiggings to catch small and median squids sizes that are exported to the European market. Also some fishing cooperatives in the north of Sinaloa, near Topolobampo, have begun fishing jumbo squid using the same fishing-pattern of Sonora State.

Landings have exceeded 100,000 t some years, but the wild abundance fluctuations result in severe uncertainty for the industry. While no satisfactory explanation is available, the variation has been blamed on environmental changes, maybe related to El Niño and La Niña (Lluch-Cota *et al.* 1999, Morales-Bojórquez *et al.* 2001, Nevarez-Martínez *et al.* 2002), while others suggest that it is related to migratory patterns or reproductive success (Klett-Traulsen 1981, Ehrhardt *et al.* 1982, 1986, Ramírez and Klett-Traulsen 1985).

6. SMALL SCALE FISHERIES

Small scale fisheries, also known as artisanal or, in Mexico, ribereñas (coastal) are difficult to define, but essentially consist of those whose catches are not large, have diverse infrastructure facilities and organization for the production, processing and marketing. Under this vague definition are considered fisheries as the Marine Stewardship Council certified spiny red lobster and the abalone fisheries, blue crabs, sea snails, clams and the large number of scale fish and sharks, skates and rays fisheries that operate with scarce infrastructure.

Nonetheless, these are the fisheries that create the largest number of jobs and produce the most of fresh fish products for the local and regional markets (Fuentes-Castellanos 1996). The target species are often considered to be overexploited, their profits are low and the social sector working in it is usually devoid of governmental support (Lluch-Cota *et al.* 2006, González-Becerril *et al.* 2007).

Knowledge about these fisheries is generally low (except for those of abalone and lobster); research has mostly been limited to the biology of the species, few on population dynamics of the target species and very little about their social and economic aspects (Cisneros-Mata 2002, INP 2006, Jiménez-Quiroz and Espino-Barr 2007). For the most, fisheries are regarded as local, not regional, with the consequence that they are not considered given their fragmented production.

In general there is urgent need to develop adequate modes and operations to manage these fisheries in the context of sustainable and responsible fishing.

Information on natural protected areas, delimitation of fishing zones, participative and transparent management are claims from the legal fishing sector to the governmental agencies, together with support programs and effective monitoring and inspection schemes (SEMARNAT 2006). There are also conflicts with the aquaculture sector, part of them because of the pollution arising from these activities, with the tourism sector stemming from infrastructure building and modification of the coastal environment and with the conservation sector, because of the establishment of no take areas on previous fishing zones (Rivera-Arriaga and Villalobos 2001).

Small scale fisheries contributed with some 13% of the fishing production in the northwest, about 108,000 annual t with a diminishing trend. Averaged west coast landings have been 9,053 t/year, including 2,268 of algae, 2,340 of sea cucumber, 1,272 of lobster, 1,252 of oysters, 929 of abalone, 538 of blue crab and 454 of snails. Gulf landings, on the other hand, amount to an estimated average of 55,538 ton/year, mostly of mojarra, spanish mackerel, mullets and sea basses. Other species represent 22,013 t.

Catches may differ according to space/temporal distribution of species (Cudney-Bueno and Turk-Boyer 1998, Espino-Barr *et al.* 2007), but factors related to varying existence of local, regional and international markets, as well as the experience and tradition of fishermen in each locality should also be taken in account (Ramírez-Rodríguez and Hernández-Herrera 2000).

The high diversity of small scale fisheries implies the usage of a wide variety of fishing gear and techniques: gillnets, line and hook, traps, etc. of which there is a limited knowledge of their efficiency and selectivity for specific target species (Ramírez-Rodríguez 1996, 1997). The National Fisheries and Aquaculture Commission (CONAPESCA) has information about 22 small scale fisheries harvesting 138 species; out of these, ten include marine scale fishes and include 79 target species.

7. SHRIMP FISHERY

The multi species shrimp fishery (blue, *Litopenaeus stylirostris*; white, *Litopenaeus vannamei* and brown, *Farfantepenaeus californiensis*; together with other less important species) was analyzed since the 1970s and found overfished by an excess of fishing power and too small mesh size in the trawl nets (Lluch-Belda 1974). Since then effort has increased further in number of large boats and their fishing power, but most of all, in the number of outboard powered pangas, now fishing for offshore shrimp. According to data in Páez-Osuna *et al.* (2003), total shrimp catch has been declining by an average of 600 ton/yr in the period of 1980-2001, while shrimp aquaculture has increased by 30% per year since 1990 and now exceeds the catch. Total shrimp production has practically doubled in the last 20 years (see Figure 2). In addition to the excess effort and small mesh sizes resulting in growth overfishing, natural variation may further impact shrimp abundance, as suggested years ago (Castro-Aguirre 1976) and recently (Castro-Ortiz and Lluch-Belda 2008). Galindo-Bect *et al.* (2000) found a significant correlation between total shrimp catch at the Upper Gulf and the rate of freshwater discharge by the Colorado River. Arias *et al.* (2004) stated that although the damming of the Colorado River may have been the principal cause of the decline in the shrimp fishery, the escalation in the number of fishing vessels and fishing gear types could have also influenced it.

Catches of offshore shrimp could improve substantially both in volume and individual sizes if fishing effort were to be reduced to adequate levels and mesh sizes regulated for optimum selectivity. While it would appear that the trend has been to let more fishers participate as a means of further distributing the benefits, it is becoming increasingly clear that such a process has involved extra financing through tax exemptions and subsidies and is no longer viable.

The impacts of the trawl fishery on the ecosystem are a major concern. Anecdotal information suggests that sweeping changes in benthic community structure have taken place over the past 30 years of these disturbances. Industrial shrimp trawling exacts a harsh toll on the Gulf's marine environment, as more than a thousand shrimp trawlers annually rake an area of sea floor equivalent to four times the total size of the Gulf. This constant bottom trawling is considered to damage fragile benthic habitats (Brusca *et al.* 2001).

Damage to the physical habitat and to non commercial, small invertebrate species has been proposed by internationally recognized specialists (Brusca *et al.* 2001), but no data are available to evaluate its extent; this is one of the areas of research that has been neglected for years. Recently, however, a comparative study between trawled and non-trawled areas has revealed no significant differences (Sánchez-González *et al.* 2009).

Conservation International Mexico (2003) has estimated that each kilogram of shrimp caught in the industrial fishery is accompanied by at least 10 kg of by-catch. Estimates for the Gulf of California have ranged from 1:2 up to 1:10 (Chapa 1976, Rosales 1976), with some larger figures at times. This proportion is similar to those reported for tropical areas around the world (1:10), while temperate ones have an average of 1:5; other fishing grounds as those of Venezuela (1:40) and Thailand (1:14) show considerably larger proportions (Cascorbi 2004).

By-catches are quite variable, depending on areas and seasons; while at the beginning of the shrimp season the proportions in catch may be lower, they tend to increase towards the end, when shrimps have been fished out. It has been shown that the proportion of by-catch in shrimp fisheries varies widely between years (Barrett and Ralph 1977, Da Silva 1986, Del Valle 1989, Solana and Arreguín 1993, Sheridan 1996).

Some species are of specific concern, such as marine turtles and juveniles of totoaba (*Totoaba macdonaldi*), both vulnerable to trawl nets. Cisneros-Mata *et al.* (1995) estimated that an average of 120,300 juvenile totoabas was killed by shrimp vessels each year from 1979 to 1987. Other icon species, such as dolphins, are rarely killed by these gears.

While the problem is similar as in the rest of equivalent areas of the world, it remains as an unsolved issue, in spite of the advances that have been made on the adoption of excluders to reduce non targeted species. The National Fisheries Institute of Mexico (INP) began developing fish excluders together with Conservation International since 1992 at the Gulf, particularly directed to the protection of totoaba (Torres and Balmori-Ramírez 1994, Balmori-Ramírez *et al.* 2003) and the efforts have continued working closely with the FAO on an international project to develop suitable excluders.

8. SHRIMP AQUACULTURE

Mexico is the second most important producer of cultured shrimp in the western hemisphere; thus, it is the most relevant aquacultural industry in the country, both in terms of volume and revenues. Up to 2005, annual production of cultured shrimp ran above 90,000 t (about 57% of the total shrimp production), with an estimated value of over 4,000 million Mex pesos (about 300 million USD).

Commercial shrimp culture began in Mexico during the mid 1980s, particularly in Sinaloa, afterwards extending to Sonora and Nayarit even though it is known that, from the climatic standpoint, the northwest is not the most favorable region in the country.

The development of the industry has been increasing steadily, incorporating new technological advances that have permitted moving from extensive to intensive operations. It is a consolidated industry, with the development of a sizeable collateral net of goods and services; nevertheless, there have been episodes of great losses, mostly due to white spot syndrome. Further, operating costs are higher than in other countries and, recently, market prices for those sizes of shrimp produced by aquaculture have tended to decline. Other problems for the industry involve environmental concerns about eutrophication by discharge waters.

Nearness to the main US market somehow balance negative factors, supported by the fact that Mexican shrimp has higher prices and demand than that of other countries. Further, within the framework of the North American Free Trade Agreement (NAFTA) there are no import tariffs. Cultured shrimp is also exported to Japan and the European Union.

There are 884 shrimp farms at the northwest, 721 of which were active along 2008. They show different intensification levels, basically grouped in three categories: extensive, semi intensive and intensive. Extensive farms have large ponds, use less than 5 postlarvae/m^2 and obtain less than one tonne per hectare (ha); feed is scarcely used or not at all. Semi intensive have smaller ponds (10–15 hectares or less), 5–20 postlarvae/m^2 with yields of 1-2 t/ha and feed is used. Finally, intensive farms are the smallest ones (2–3 ha or less), use more than 20 postlarvae/m^2, have yields of more than 3 t/ha, use feed and agitators.

Depending on temperature seasonality, farms run one or two production cycles, the warmer season being the most favorable. Most farms sell the product directly, few ones to their own, integrated plants.

9. STATUS OF FISHERIES

Sala *et al.* (2004) stated that coastal food webs have been "fished down" in the Gulf, based on interviews with fishers, fisheries statistics and field surveys, looking at the effects described by Pauly *et al.* (1998). According to these authors, the decline in fish stocks has been accompanied by a marked shift in the composition of the coastal fishery and a decrease in the maximum individual length of fish catches by approximately 45 cm in 20 years. Large predatory fishes were among the most important catches in the 1970s, but became rare by 2000. Species that were not targeted in the 1970s have now become common catches. However, other studies based on widely accepted methodology have shown opposite results, concluding that there is no sign of fishing down (Pérez-España 2004, Arreguín-Sánchez 2005).

Arias *et al.* (2004) recalls that the American Fisheries Society's official list of marine fish at risk of extinction includes 6 species of large groupers and snappers, 4 of which are endemic to the Gulf of California and adjacent areas. Of these, 2 are regarded as endangered, while the remaining 4 are considered as vulnerable, given the fact that these species are sensitive to overharvesting because of late maturity and the formation of localized spawning aggregations (Musick *et al.* 2000). Large, slowly growing fish are particularly evident in showing the effect of fishing on a population: decrease in abundance and in average individual size; both are unavoidable consequences when aiming at maximizing yield. What occurs in the Gulf of California is the same process as those in Puget Sound, Florida and the southern Gulf of México, the other "hot spots" described by Musick *et al.* (op. cit.).

Of particular concern has been the totoaba, a very large endemic species that was heavily fished during the 1930s–1940s. Although overfishing has been blamed for the early decline of the fishery, the reduction in the flow of the Colorado River may have been a major cause of depletion through the alteration of the estuarine habitat of the river delta, its normal spawning and nursery area (Arias *et al.* 2004). The totoaba fishery declined since 1970 due to diminishing populations and to restrictions imposed (in 1975) when catch levels threatened the population. Despite closures, the gill net fishery continues catching juvenile totoabas as by-catch on a small-scale.

Gill nets also incidentally capture vaquitas and sea turtles. Between March 1985 and January 1994, 76 vaquitas were killed incidentally in totoaba gill nets (D'Agrosa *et al.* 1995). The total estimated incidental mortality caused by the fleet of El Golfo de Santa Clara was 39 vaquitas per year, over 17% of the most recent estimate of population size (D'Agrosa *et al.* 2000). The vaquita population was estimated to be less than 600 (Jaramillo-Legorreta *et al.* 1999), and recent estimates set the number at 245 (CI= 68 – 884; Gerrodette *et al.* 2011) therefore, considering normal replacement rates (maximum rate of population growth for cetaceans is of 10% per year), this incidental loss may not be sustained. Vaquitas, on the other hand, have been a very restricted population since they were described, at least. CONABIO (2005) reports results of several projects suggesting that a number of genetic and morphological characteristics point at a population with very restricted genetic diversity.

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THE ARTISANAL FISHERY OF BAHÍA DE LOS ÁNGELES AND ÁNGEL DE LA GUARDA ISLAND, GULF OF CALIFORNIA, IN 1995

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Bahía de los Ángeles is a small village in the Gulf of California, northwestern Mexico, devoted to fishing inside the bay and around nearby islands. Fishing started in the 1930s, and has changed in response to resource abundance, market demands, accessibility, and legal restrictions. We studied fishing there from 1993 to 1995, but had generated data also during the previous 11 years. Most fishing was done by "free fishermen," working out of fishing camps at 59 insular and 8 coastal sites. Fishing included 58 species of fish of 34 families. Between 1984 and 1996, fishing volumes fluctuated between 306 and 798 ton / year, without any trend. Although, scalefish produced most of the landings, sea cucumber was important. Multispecies fishery was highly efficient in the use of the catch. Fishing depths were usually 10.2 to 89.5 fathoms, but could be as deep as 200 fathoms. Gillnets and three-layer trammel nets were the most common fishing gear. In any single year, 8–15 fishing zones, out of 26, were used. No rules existed as to exclusive access to resources by the local community, although they could have helped to reduce fishermen competition, reduce the risk of resource depletion, and reduce by-catch spoilage.

1. INTRODUCTION

The town of Bahía de los Ángeles (28°56'N and 113°31'W) is a small fishing village within a large bay bearing the same name, on the western side of the Gulf of California, northwestern Mexico. Fishing is carried out inside the bay, as well as around the island of Ángel de la Guarda, in Canal de Ballenas, and in Canal de Salsipuedes. During the late 1930s and the 1940s fishing and mining attracted people to the then little populated area of Bahía de los Ángeles (Caroline Shepard, long time resident of Bahía de los Ángeles and director of the local museum, pers. comm., 1997). At this time, fishing was centered on totoaba (*Totoaba macdonaldi*), for its swimming bladder; sharks, for their liver oil, and sea turtles, for their meat (especially the Olive Ridley (*Lepidochelys olivacea*), and the caguama prieta (*Chelonia mydas*; Arvizu-Martínez, 1987).

Until the construction of the transpeninsular highway, and the paved road that links this to Bahía de los Ángeles, transport of the products to Ensenada, Tjuana, and the United States was slow, hindering commercial fishing. Construction of these roads promoted increases in fishing volume and number of species targeted for commercial fishing. Although fishing in this area is important, and the region has attracted the attention of the academia, commercial fishing had not been analyzed. The objective of this study was to characterize the artisanal fishery of Bahía de los Ángeles and nearby Ángel de la Guarda island. Almost 20 years have elapsed since our study, and conditions and pressures on fishing, as well as other economic activities, have changed in Mexico. Although our study is focal, it reflects one of the fishing realities in the central Gulf of California, at the time. Our study, along with that of Chenaut (1985), will serve as a reference with which to measure such changes, current or future.

2. METHODS

2.1. Study area

This study includes the waters in Bahía de los Ángeles and those surrounding Ángel de la Guarda island, including Canal de Ballenas and Canal de Salsipuedes (see Figure 1). We include the villages of Bahía de los Ángeles, Las Ánimas, San Rafael and San Francisquito. The area is in the arid Gulf coast of Central Baja California. The climate of this region is arid, with mean annual temperature of 22.8°C (range 15–33.6°C), and mean annual precipitation of 83 mm (range 9–235 mm; INEGI, http://mapserver.inegi.gob.mx). The waters in the area exhibit year-round upwelling in Canal de Ballenas and Canal de Salsipuedes (Álvarez-Borrego 1983), which leads to an important concentration of plankton and high diversity and abundance of fish. Aridity of the region and lack of sources of fresh water prevent agriculture, and the only economic activities are fishing and tourism, and, in the past, mining.

In 1990 Bahía de los Ángeles had 443 inhabitants (INEGI 1991), 250 of which were full-time residents. Four years later the number of full-time residents had increased to 378, but the floating population stayed around 200 people. In 1997, the total population was between 600 and 750 people (C. Shepard, com. pers., 1997; R. Espinoza, com. pers., 1997), making it the second most populated community in

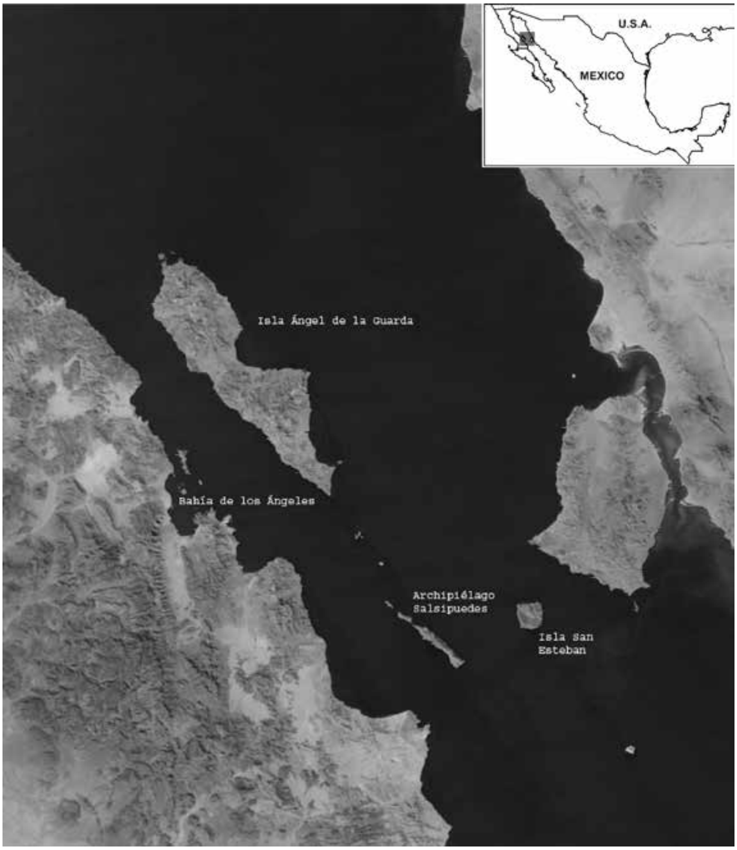

FIGURE. 1. Study area.

the Midriff island region of the Gulf of California, with about 11% of the population of this region. This increase resulted from the immigration of people from the states surrounding the Gulf of California, other than the state of Baja California (Bourillón-Moreno 1996).

Both in 1990 (INEGI 1991) and in 1994 (AZ-G, unpubl. field notes) there were slightly more males than females in Bahía de los Ángeles (52 and 54%, respectively). In 1994, 36% of the males (70 people) were fishermen. They were between 16 and 80 years of age, but 85.7% were 45 years or younger. This age composition differs from that during the 1980s along the western coast of Baja California, where ages of fishermen were between 12 and 29 years (Avilés-Muñoz and Figueroa-Ramírez 1989). During our study, males younger than 16 years of age, in Bahía de los Ángeles, attended school.

Whereas 52.8% (n = 53) of the fishermen between 16 and 30 years of age of Bahía de los Ángeles were employed in fishing only part-time, 66.7% of those older than 30 years (n = 63) were semi-permanent fishermen. Most of older males in the community were full-time fishermen at one time, and those that remained active advised younger fishermen in the reparation of fishing gear.

Males that were not fishermen worked as masons and painters, merchants, laborers, mechanics, and cowboys. When fishing was bad, many fishermen tried to get jobs as construction workers (in masonry and painting). Similar to other regions in Mexico, "free fishermen" (those not belonging to any fishers cooperative) did not own boats, and often combined fishing with other jobs elsewhere, especially when fishing was unproductive (see Gatti 1986).

The fishing population of the Bahía de los Ángeles region included 23 permit-holders, and 47 free fishermen (which don't have permits). There were also 233 registered foreign (to the region) fishermen (Subdelegación Federal de Pesca, December 1994). Free fishermen sold their catch on the beach or directly to the permit-holders, and their products could be recorded under the name of the later, or not be recorded at all.

2.2. Field work

Between June 1993 and June 1995, AZ-G made 14 visits to the region. On the first visit he selected adequate informants (*sensu* Hernández and Ramos 1976), based on previous acquaintance with some fishermen. He made some informal interviews and participated directly in fishing trips. To characterize the fishing population we used partial results of a census made in the spring of 1994 by the Instituto para el Desarrollo Integral de la Familia (Mexicali, BC, unpublished). We also used the information gathered by AZ-G during 11 years of field work previous to this study.

Fishing activity was characterized based on the volume of landed catch (and recorded), fishing gear used, and the fishing zones, methods and seasons. Species fished were identified in situ with the aid of field guides (Miller and Lea 1972, Castro 1983, Eschmeyer and Herald 1983). Specimens were photographed for later identity checks, and the fishermen were interrogated about the species that were captured. We interviewed 23 active fishermen, 2 fishery inspectors, and the director of the local museum, the delegate (representing the municipal president), two local physicians, several elder fishermen, and other persons with a good knowledge of the area.

Although a complete record of the actual captures was not available, the official statistics, based on the reports by the fishermen themselves, were good indicators of capture dynamics. We reviewed this information for the period between 1984 and 1996 at the Subdelegación Federal de Pesca, Secretaría del Medio Ambiente, Recursos Naturales y Pesca (SEMARNAP), in Baja California. Tallying the capture data from highest to lowest yearly volume, we considered those species that accounted for 90% of all capture volume as the main fishery resources. Information on fishing zones derives from seven years of data (1990–1996). For each of the zones we determined the main fishing target species in the same manner as above.

3. RESULTS AND DISCUSSION

3.1. Labor organization

Most fishing was carried out by free fishermen employed by others, as it occurs elsewhere in Baja California (Avilés-Muñoz and Figueroa-Ramírez 1985, 1989). These fishermen did not belong to any formal organization and sold their fishing products to one of the permit-holders. Therefore they were dissociated from the market, contrary to fishermen affiliated to cooperatives in Sonora and Sinaloa (McGoodwin 1987) and the west coast of Baja California (Avilés-Muñoz and Figueroa-Ramírez 1989).

There were two basic labor arrangements. One was that of "employed fishermen," fishermen that made individual arrangements with the permit-holders and fished for a daily salary, a commission, and/or a payment for amount worked. Under these arrangements, the permit-holders provided fishing equipment (skiff, motors, fuel and water containers, fishing gear, ice chests, etc.), and bought the produce. Their fishing was directed at specific target species.

The second arrangement, "work teams," involved fishermen that owned some equipment (Gatti 1986, Avilés-Muñoz and Figueroa-Ramírez 1987, 1989). There were few fishermen in Bahía de los Ángeles organized this way. They had a much more multi-specific catch and fished closer to the village than the previous fishermen.

The social/fishing environment within the community was notoriously little conflictive and exhibited strong inter-personal relations. In both cases the teams were commonly integrated by relatives and friends.

3.2. Fishing camps

The continuous increases in the price of gasoline and motors promoted an increase in the use of islands and islets of the region, to increase fishing ranges. Originating from Bahía de los Ángeles (at least 70 individuals), San Rafael (approximately 7), Las Ánimas (5), San Francisquito (13) and El Barril (10), most fishermen used different areas of the Ángel de la Guarda archipelago to establish temporary fishing camps at 59 sites on the islands (including the islands of San Esteban and San Pedro Mártir), and 8 sites on the coasts of Baja California. These camps consisted of one

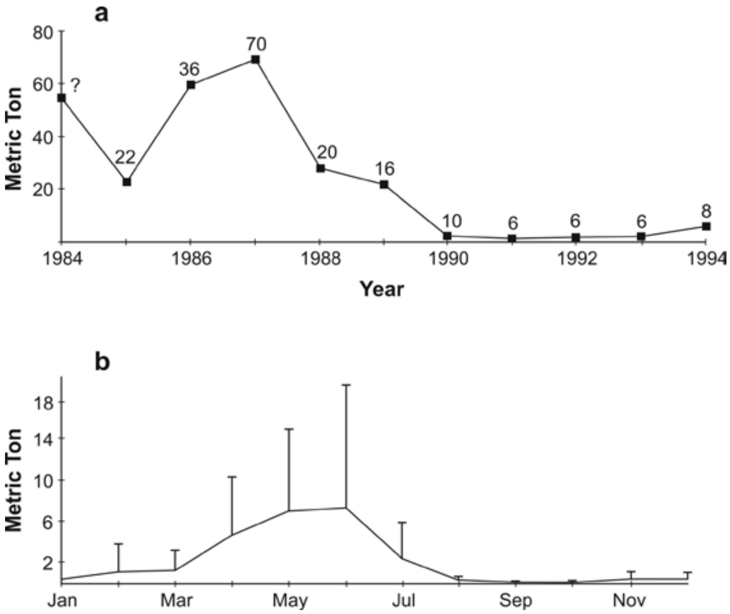

FIGURE. 2. Landings of Rooster hind from Puerto Refugio.

or more shacks (made from wooden poles and planks, cardboard, and plastic sheets), that harbored between 4 and 7 fishermen each, and/or were used to store up to 6–7 fishing equipments.

Fishing camps on the peninsular shore were used continuously for several months by fishermen from other places, but seldom by local fishermen. Island camps were seasonal, visited less frequently than peninsular ones, and non-periodically throughout the year. The smallest of these camps was less than 25 m^2, while the largest was over 6,700 m^2, and they all were close to fishing zones. Most camps had only a shack or cleared areas surrounded by rocks where fishermen stayed from some hours to a few days.

A fishing camp was set up or not depending on the abundance of a resource or the demand for it. For example, during the mid 1980s, baqueta (*Epinephelus acanthistius*) fishery was based at Puerto Refugio (see Figure 2a), in the Spring and Summer of every year (see Figure 2b). The fishing camp, peopled by an average of 24 fishermen, consisted of six cabins and gasoline-based electric generators (A Z-G unpublished data). In the spring and summer of 1987, at its highest occupancy, it had 70 fishermen, 30 skiffs, and 4 small boats (12 ton of storage capacity and manned by 4–6 people each).

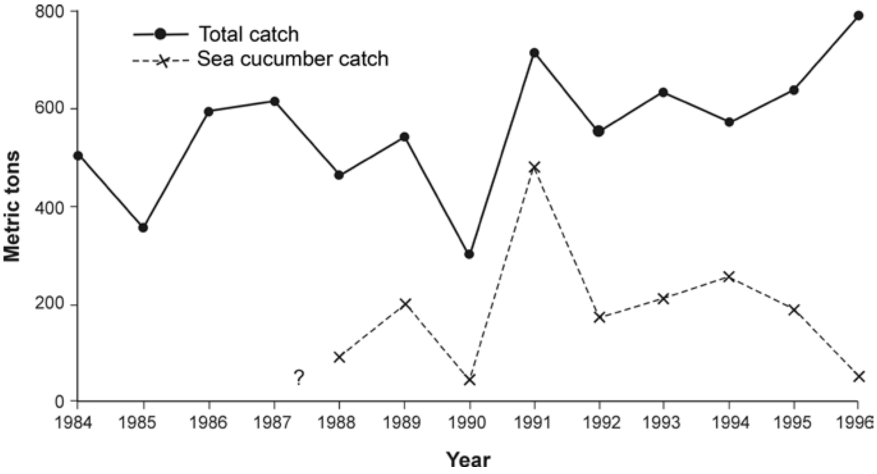

FIGURE. 3. Landings of fish at Bahía de los Ángeles.

Many fishermen alternated in their use of the camps, in agreement with the movements of fish stocks, and any fishermen could use a number of camps throughout the year, and a single camp could be used by different fishermen in succession. This style of using the islands of the region by fishermen has existed at least since the 1940s (José María González, pers. comm., June 1985). Not all fishermen were respectful for the camps, and local fishermen complained that fishermen coming from Sonora, across the Gulf of California, left behind abundant trash in them.

3.3. Fishing catch volumes

Reported fishing catch volumes for Bahía de los Ángeles between 1984 and 1996 fluctuated between 306 and 798 ton / year, averaging 535. There was no significant trend during the 1984-1994 period (p = 0.0748, r2 = 0.26, based on the logarithms of capture volumes; see Figure 3). Scalefish fishery ("pesca de escama") produced an average 400 ton / year between 1984 and 1996 (range = 233-740). This fishery dropped significantly during 1984–1991 (p = 0.034, r2 = 0.554; see Figure 3), but increased significantly from 1991 to 1996 (p = 0.042, r2 = 0.684).

Total catch volumes include "scale fish" fishing, as well as sea cucumber (*Isostichopus fuscus* and *I. inornata*). Captures of the later, however, began to be recorded in 1988, although its fishery in the entire Gulf of California began in 1985. From 1988 to at least 1994 the development of this fishery greatly influenced the fishing in the region. Its capture increased from 92.754 ton in 1988 to 378.904 ton in 1989. Sea cucumber represented 15.7% of total fishing volume in 1990 and 67.6% in 1991.

These changes reflected the increased demand of the product by the foreign markets, especially those of Korea and Japan (Secretaría de Desarrollo Económico 1994), and were completely marginal to the population dynamics of the species. In 1994 the "hard sea cucumber" (*I. inornata*) was officially banned from fishing in the Gulf (Diario Oficial de la Federación 1994), and catch of sea cucumber altogether was dropped from the records.

Sea cucumber was captured by the same local fishermen that, at other times, fished scale fish, but also by fishermen from Sonora and Baja California Sur. When the sea cucumber populations begun to be depleted, fishermen competed intensively with each other, and improved their equipment as to reach cucumber beds farther from their locations of residence, and to remain there for longer times.

Capturing sea cucumbers on shores of other communities generated many conflicts between fishermen, as local fishermen claimed exclusive rights over the resources adjacent to their communities. In addition to causing competition between fishermen, this single-resource production (based on the high market price and directed at export), caused intensive use, and impacts, on the shores of some islands (Bourillón-Moreno 1996). Official protection of the hard sea cucumber apparently caused fishermen to return to their traditional fishing resources. As a secondary consequence, the conflicts that had developed among fishermen smoothed, and the amount of trash at fishing camps diminished.

3.4. Fishery resources and seasonality

The local, artisanal fishery included many neritic species, fished in small amounts, mostly near the coast. We recorded 58 species of fish of 34 families that were included in the catch (see Table 1). Of these, 48 (81.4%) were commercial species: 40 (67.8%) for direct human consumption, 2 (3.4%) for consumption and as bait, and 3 (5.1%), exclusively for bait. The other 11 species (18.6%) were captured incidentally. Of the 48 targeted species, 13 were the most important resources, based on catch volumes.

Fishermen exhibited high efficiency in the use of their catch and little wastage, when fishing multispecifically. This style of fishing was carried out year-round, and included resident fish species as well as species present seasonally. When year-round fishes were targeted, fishermen usually specialized in specific fishing zones, moving between them to improve their success.

3.5. Fishing gear

Fishing was carried out at depths ranging from 10.2 to 89.5 fathoms (see Table 2), although at certain sites southwest and northwest of Ángel de la Guarda they could fish as deep as 200 fathoms. There was no relationship between fishing depth and

TABLE 1. Fish species captured by Bahía de los Ángeles fishermen. 1994. ? = denotes that identification was not certain, * = indicates species informed by fishermen, but not recorded by us, Tar. = targeted, Inc. = incidental capture, E.I. = economically important, L.C. = local consumption.

Family	Scientific name	Common name	Notes
Alopiidae	*Alopias superciliosus*	Perro, judio, chango, zorro, bigeye thresher	Tar., E.I.
Carcharhinidae	*Carcharhinus leucas*	Tiburón toro, gambuzo, bull shark	Tar., E.I.
	C. limbatus	Volador, cazón, blacktip shark	Tar., E.I.
	Galeocerdo cuvier *	Tiburón tigre, tintorera, tiger shark	Tar., E.I.
	Negaprion brevirostris *	(Tiburón limón, tiburón amarillo, lemon shark)	Tar., E.I.
	Prionace glauca	Tintorera, tiburón azul, blue shark	Tar., E.I.
Ginglymostomatidae	*Ginglymostoma cirratum* ?	(Tiburón gata, nurse shark)	Inc.
Heterodontidae	*Heterodontus francisci*	Gato, cornudo, horn shark	Inc.
Lamnidae	*Isurus oxyrinchus*	Tiburón mako, alecrín, bonito shark, shortfin mako	Tar., E.I.
	Carcharodon carcharias	Tiburón blanco, great white shark	Tar., E.I.
Scyliorhinidae	*Cephaloscyllium ventriosum*	Swell shark	Inc.
	Parmaturus xaniurus	Filetail catshark	Inc.
Sphyrnidae	*Sphyrna lewini*	Tiburón martillo, cornuda, scalloped hammerhead	Tar., E.I.
Squatinidae	*Squatina californica*	Angelito, Pacific angel shark	Tar., E.I.
Triakidae	*Mustelus lunulatus*	Tiburón mamón, Sicklefin smooth-hound	Inc., E.I.
Gymnuridae	*Gymnura marmorata*	Raya mariposa, California butterfly ray	Inc.?, E.I.
Mobulidae	*M. birostris*	Giant manta	Inc., L.C., bait
Myliobatidae	*Myliobatis californica* *	Tecolote, raya gavilán, manta, bat ray	Inc.
Rajidae	*Raja* sp.	Raya, skate	Inc., E.I.

Family	Scientific name	Common name	Notes
Rhinobatidae	*Rhinobatos productus*	Pez guitarra, shovelnose guitarfish	Inc.?, E.I.
	Zapteryx exasperata	Pez guitarra, banded guitarfish	Inc.
Chimeridae	*Hydrolagus colliei*	Spotted ratfish	Inc.
Diodontidae	*Diodon holocanthus*	Pez erizo, long-spine porcupinefish	Inc.
Balistidae	*Balistes polylepis*	Cochi, cochito, finescale triggerfish	Tar., E.I.
Carangidae	*Seriola lalandi*	Jurel de Castilla, jurel, yellowtail amberjack	Tar., E.I.
Clupeidae	*Ophistonema libertate*	Sardina machete, Pacific thread herring	Tar., bait
	O. medirastre	Sardina, Middling thread herring	Tar., bait
Coryphaenidae	*Coryphaena hippurus*	Dorado, common dolphinfish	Inc., L.C., bait
Engraulidae	*Engraulis mordax*	Northern anchovy	Tar., E.I.
	Anchoa helleri	Gulf anchovy	Tar., E.I.
Gerreidae	*Eucinostomus* sp.	Mojarrita plateada, flagfin	Tar., bait
Haemulidae	*Anisotremus davidsonii*	Sargo	Tar., E.I.
Istiophoridae	*Istiophorus platypterus*	Pez vela, Indo-Pacific sailfish	Inc., E.I.
Labridae	*Thalassoma lucasanum*	Vieja, Cortez rainbow wrasse	Tar., E.I.
Malachantidae	*Caulolatilus princeps*	Blanco, ocean white fish	Tar., E.I.
Merlucciidae	*Merluccius productus*	Merluza, north Pacific hake	Tar., E.I.
Moronidae	*Stereolepis gigas*	Pescada, giant sea bass	Tar., E.I.
Mugilidae	*Mugil cephalus*	Lisa, liseta, flathead mullet	Tar., E.I.
Paralichtyidae	*Paralichthys aestuarius*	Lenguado, halobato, Cortez halibut	Tar., E.I.
Scianidae	*Cynoscion parvipinnis* ? *	(Curvina, shortfin corvina)	Tar., E.I.
	C. xanthulus	Curvina, Orangemouth corvina	Tar., E.I.
Scombridae	*Katsuwonus pelamis*	Bonito, skipjack tuna	Tar.?, E.I.
	Sarda orientalis ? *	(Bonito, Mexican bonito)	Tar.?, E.I.
	Scomber japonicus	Macarela, chub mackarel	Tar., E.I.

Family	Scientific name	Common name	Notes
Scombridae (cont'd)	*Scomberomorus sierra*	Sierra, Pacific sierra	Tar., E.I.
Scorpaenidae	*Scorpaenodes xyris*	Rainbow scorpionfish	Inc.?, E.I.
	Sebastes sp.?	(Rockfish)	Inc.
Serranidae	*Diplectrum euryplectrum* ? *	(Cabicucho, bighead sand perch)	Tar.?, E.I.
	D. Pacificum *	Cabaicucho, inshore sand perch	Tar.?, E.I.
	Epinephelus acanthistius	Baqueta, Rooster hind	Tar., E.I.
	E. analogus	Pinta, cabrilla pinta, spotted grouper	Tar., E.I.
	E. itajara	Mero, goliath grouper	Tar., E.I.
	Mycteroperca jordani	Baya, Gulf grouper	Tar., E.I.
	M. rosacea	Cabrilla sardinera, leopard grouper, golden grouper	Tar., E.I.
	M. xenarca	Garropa, broomtail grouper	Tar., E.I.
	Paralabrax auroguttatus	Extranjero, lucero?, goldspotted sand bass	Tar., E.I.
	P. maculatofasciatus	Arenera, cerotera, cabrilla, spotted sand bass	Tar., E.I.
Synodontidae	*Synodus* sp.	Chile, lizardfish	Inc.

the number of species captured.

Several types of fishing gear were used. Gillnets were placed either straight or used to circle fish were placed on the surface, in mid-water or on the bottom. Generally, they had only one layer, but sometimes three-layer trammel nets ("redes atrasmalladas" or "trasmallos") were used. In Bahía de los Ángeles, fishermen often constructed an artisanal, rustic trasmallo, using two nets and pieces of cord along the breadth of the net at fixed distances. The later were intended to catch the fish without killing them. Single lines were either hand-held or on a pole and rod, either with hooks or with curricanes. Longlines were also used. The gear was completed with devices to hurt and retain the fish, like harpoons, hooks and clubs.

The most common gillnets were of monofilament with 3", 3.2", 4.5", 5" and 8" mesh, and of cotton twine with 1.5" and 5.1" mesh. These nets were commonly between 120 and 180 fathoms in length. Fishing lines were of nylon, of different caliber.

TABLE 2. Main fishing zones for the artisanal fishery based at Bahía de los Ángeles, Gulf of California, Mexico, in 1995.

Fishing zone	Depth	# species		# species / year			Principal species	
	phathoms	Total	90%	Mean	S.D.	n	resources	%
Bahía de los Ángeles	10.2 (9.9)	>65	13	37.3	6.3	7	sea cucumber, shark	56.8
Isla Ángel de la Guarda	33 (52.9) to 231.2 (181.6)	>30	7	12	8.5	7	sea cucumber	65
Bahía San Francisquito	64 (57.9)	>20	2	7.2	3.5	6	sea cucumber, shark	63
Bahía de las Animas	53 (84.5)	37	16	20.6	6.5	5	sea cucumber, algae octopus, flathead mullet	53.9
Isla Las Ánimas	89.5 (49.6)	26	10	12.8	7.3	4	sea cucumber, shark, yellowtail amberjack	59.2
El Barril		33	11	15	5.3	6	flatfish, shark, ocean white fish	53.8
Punta La Gringa		17	35.3	5.2	6.3	5	sea cucumber, scallops	65.1
Ensenada de Guadalupe	45.7 (27.8)	21	28.6	7.2	5.1	6	sea cucumber	51.8
Isla Coronado	15.8 (15.8)	23	26.1	14.5	6.4	2	sea cucumber, shark	69.4
Puerto Refugio	33.8 (31.5)	26	50	8.5	9.1	4	sea cucumber, shark, gold spotted sand bass, yellowtail amberjack	56.8
Puerto Los Choros		1	100	1		1	sea cucumber	100
La Víbora	41.9 (31.6)	24	33.3	8.3	5.1	4	shark	52.4
Bahía San Rafael	48.1 (67.1)	>33	48.5	11.8	8.8	6	octopus, flatfish, gold spotted sand bass, ocean white fish, Sicklefin smooth-hound	54.5

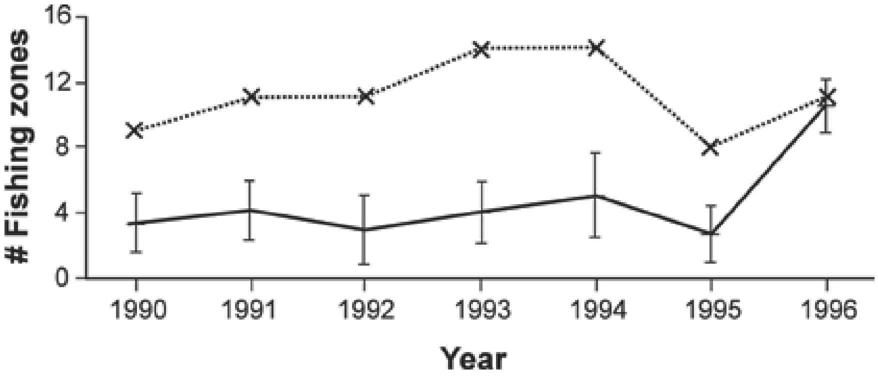

FIGURE 4. Total (dotted line) and average (solid line, ± S.D.) number of fishing zones that provided ≥ 90% of total resources each year.

3.6. Fishing zones

The names used by fishermen to fill in their landing reports did not necessarily reflect the exact fishing zone. Often, the geographical definition of such names was very ambiguous. By accompanying fishermen in their activities, we delimited the fishing zones with higher use.

The fishing office at Bahía de los Ángeles has 26 declared fishing zones, 15 of them in our study area; 3 are clearly outside it, and the remainder were not locatable. Thirteen of these fishing areas were the most important (see Table 2). During the years before our study the number of fishing zones had increased, apparently due to: 1) newer equipment (motors over 100HP), 2) an apparent depletion of some resources in traditional fishing zones and, 3) an increase in the number of fishermen and fishing skiffs in the region, leading to more competition and the exploration of new zones.

Sea cucumber and sharks were fished in 76.9% and 53.8% of the fishing zones, respectively. The other resources were captured in less than 16% of the fishing zones. The largest diversity in fishing products came from the bays and coasts (see Table 2), rather than from open waters. From 1990 to 1996 the fishing zone that provided most product was Bahía de los Ángeles itself (73.6%, see Table 2). The other fishing zones provided only small catches: waters adjacent to Ángel de la Guarda island (6.7%), Bahía de San Francisquito (5.2%), Bahía de Las Ánimas (3.6%), waters near Isla Las Ánimas (3.5%), and El Barril (2.9%)

In any single year, between 8 and 15 fishing zones were used, and not all fishing zones were used all years (see Figure 4). The fact that in 1993 and 1994 15 and 14 zones, respectively, were used (previously no more than 11 had been used in any single year) was due probably to the El Niño Southern Oscillation event that caused low captures, forcing fishermen to roam through all zones. The number of fishing zones used in any single month increased from 3.3 (± 1.7, n = 12) to 10.5 (± 1.6, n = 12) from 1990 to 1996, and between 1990 and 1995 only 26 to 37% of all zones were used in any given year, whereas 95% of them were used in 1996 (see Figure 4).

4. FINAL COMMENTS

The fishing community of Bahía de los Ángeles did not escape from the demographic events and problems faced by other rural fishing communities that are isolated and have serious limitations in their basic services. In some areas of the Upper Gulf of California, were fishing communities are close to each other, there is an informal control over fishing territories. Foreign fishermen were allowed to participate only as crew of fishing teams, and must pay a fee to do so (Cudney-Bueno and Turk 1998). No such territorial control was evident in Bahía de los Ángeles during our study. Here, fishing represented the permanent source of income for local fishermen, but only in occasions, a partial source of income for foreign fishermen. Also, whereas local fishermen fish for self-consumption and for within-community sale, the foreign fishermen were market-oriented and delivered their produce to intermediaries or to permit-holders. This lack of fishing zone control has affected local fishermen when highly-priced resources are fished.

Therefore, the disadvantages of open fishing zones should be evaluated, especially when it is used for monospecific exploitation based on species with high commercial value, rather than for their local use. Such fishing promotes spoilage of the by-catch, which, because of its lower value, is discarded. Regulation of the fishery should consider territorial exclusivity rights, or at least fishing priority, for the local fishermen. This might help to reduce competition for resources and in reduce the risk of their depletion.

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Exploring Mexico's northwest, the Baja California Peninsula, its surrounding oceans, its islands, its rugged mountains, and rich seamounds, one feels diminished by the vastness and the greatness of the landscape while consumed by a sense of curiosity and awe. In a great natural paradox, we see the region's harsh arid nature molded by water through deep time, and we feel that its unique lifeforms have been linked to this desert and sea for thousands of years, as they are now.

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Elisabet V. Wehncke

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