


CONSERVATION SCIENCE IN MEXICO'S NORTHWEST

ECOSYSTEM STATUS AND TRENDS IN THE GULF OF CALIFORNIA




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EDITORS


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.

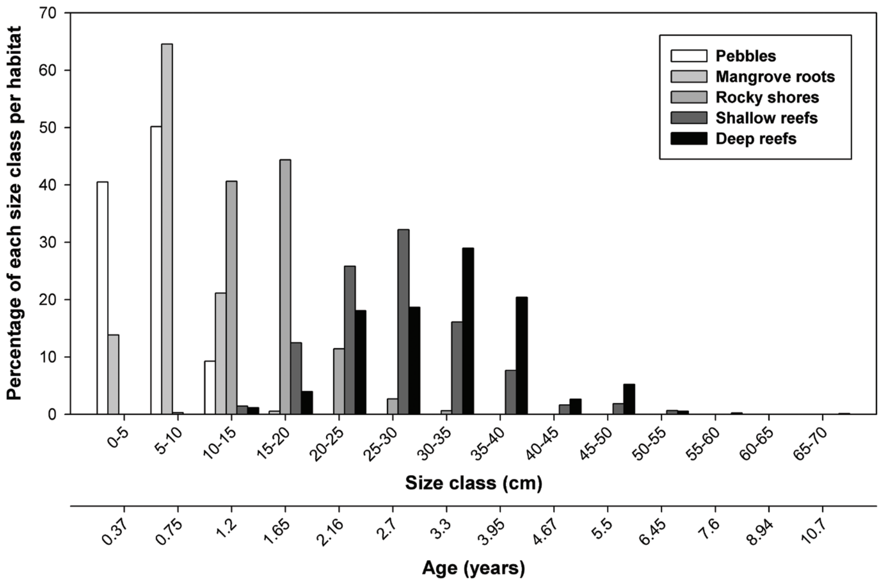

FIGURE 1. Significant differences in size classes ontogenetic patterns of habitat use for the yellow snapper ($X^2 = 8.29$, $p < 0.01$). Data are percentage of the abundance of each size-class in the underwater surveys per habitat. Age was calculated using von Bertalanffy exponential growth model with 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

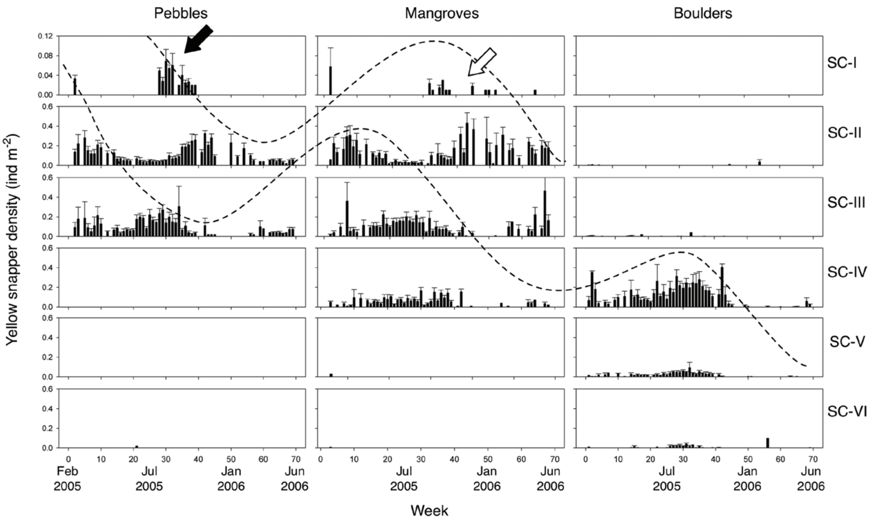

FIGURE 3. Mean and standard error for the six size classes (see Table 1), in the three habitats surveyed in Balandra mangrove (see Figure 2). Note that density scale of SC-I is different from the rest of size classes, in order to show the magnitude of settlement in pebbles (black arrow) and the second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

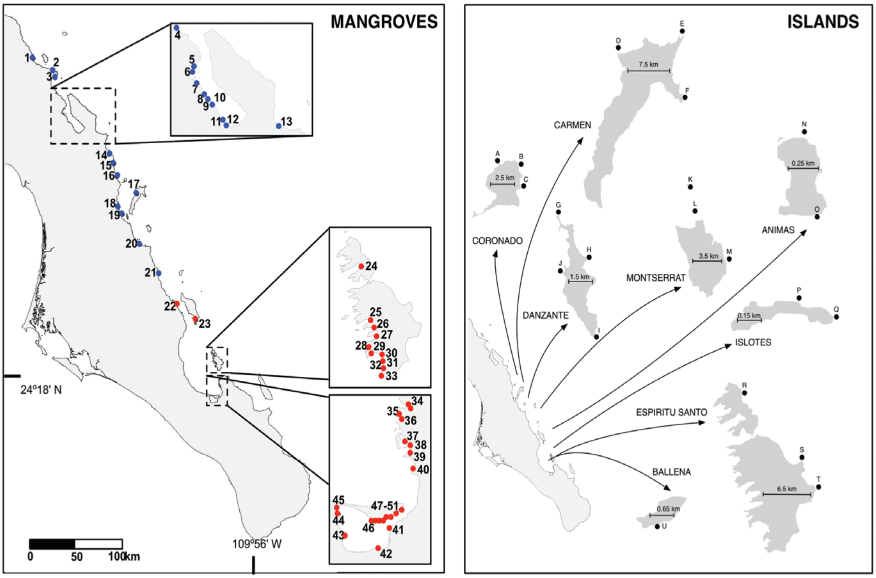

FIGURE 4. Map of the southern part of the Baja California Peninsula showing the location of all mangrove patches sampled in 2007; and the islands that have been monitored since 1998.

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	Buenaven-tura	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

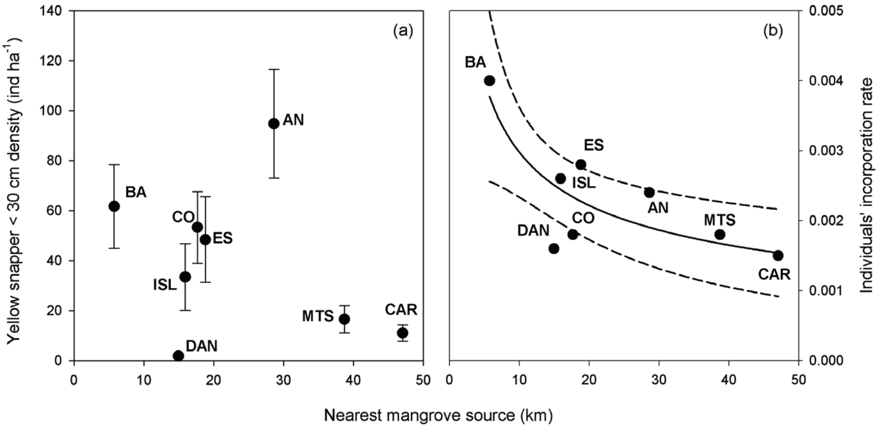

FIGURE 5. (a) Relationship between distance to the nearest mangrove source and the density of juvenile yellow snappers (*Lutjanus argentiventris*). Islands with a mangrove source less than 20 km away had on average, more than 40 individuals per hectare while islands with a mangrove source farther than 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.

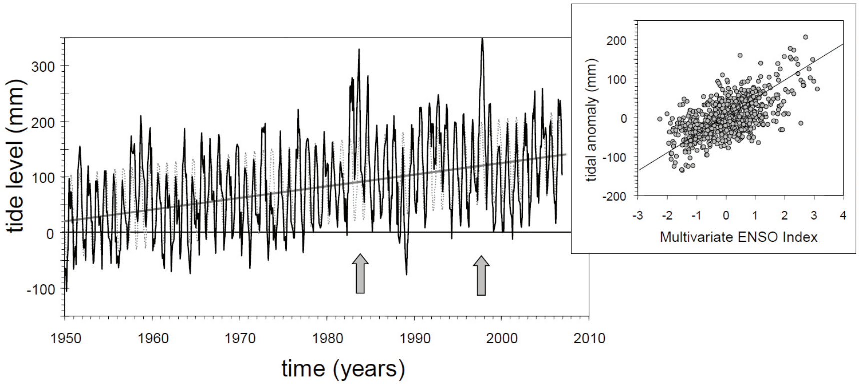

FIGURE 6. Monthly mean sea-level values for the Pacific coast of Baja California. The data line in black shows the averaged values of the three tide stations (Scripps, San Diego, and Los Cabos), arbitrarily taking the mean tidal level for year 1950 as the baseline origin. The straight line in gray indicates 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

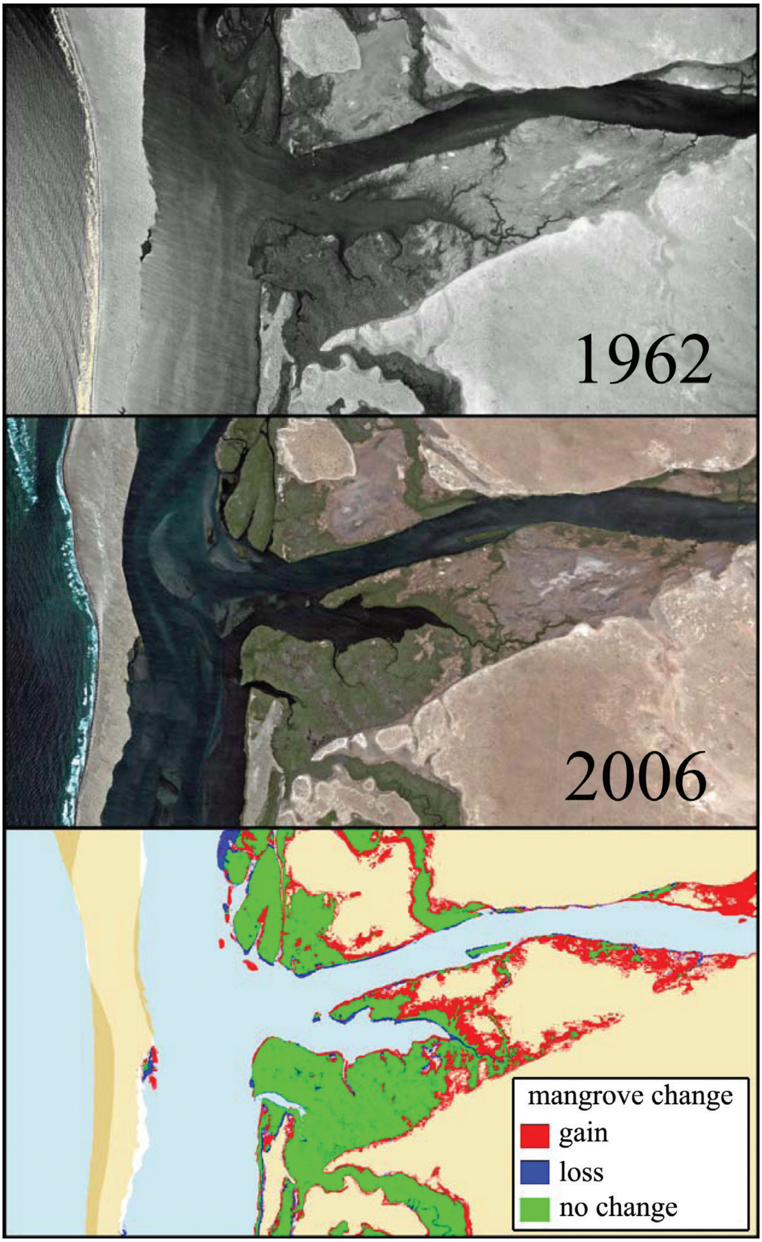

FIGURE 7. The effects of sea level rise are visible from above in Boca de Santo Domingo, Bahía Magdalena: The top plate shows an aerial photograph taken in 1962, the middle one, a GoogleEarth image from August 2006. The image at the bottom highlights the differences between the two timed photos. With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

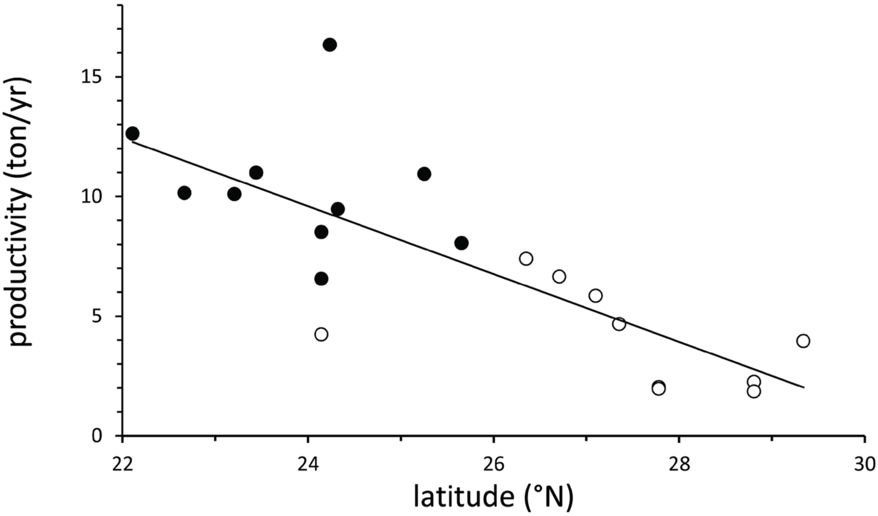

FIGURE 8. Relationship between latitude and productivity in mangroves around the Gulf of California, in northwestern Mexico. Open dots, mangroves with *Rhizophora mangle*, black dots mangroves with *Avicennia germinans* and/or *Laguncularia racemosa* ($r^2 = 0.62, p < 0.0001$).

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 25º, 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 25º, 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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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.

These landscapes of fantasy and adventure, this territory of surprising, often bizarre growth-forms and of immense natural beauty, has inspired a wide array of research for over two centuries and continues to inspire the search for a deeper knowledge on the functioning, trends, and conservation status of these ecosystems in both land and ocean.

This book offers a compilation of research efforts aimed at understanding this extraordinary region and preserving its complex richness. It is a synthesis of work done by some exceptional researchers, mostly from Mexico, who indefatigably explore, record, and analyze these deserts and these seas to understand their ecological processes and the role of humans in their ever-changing dynamics.

Elisabet V. Wehncke

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