Mangroves in the Gulf of California increase fishery yields

Octavio Aburto-Oropeza*†‡, Exequiel Ezcurra§, Gustavo Danemann¶, Víctor Valdez¶, Jason Murray‖, and Enric Sala*,**

*Center for Marine Biodiversity and Conservation, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0202; †Departamento de Biología Marina, Universidad Autónoma de Baja California Sur, Carretera al Sur Km 5.5, La Paz, Baja California Sur, CP 23081, México; §San Diego Natural History Museum, P.O. Box 121390, San Diego, CA 92112-1390; ¶Marine Conservation and Sustainable Fisheries Program, Pronatura Noroeste A.C., Calle Décima No. 60, Zona Centro, Ensenada, Baja California, CP 22800, México; ‖Department of Economics, Moore School of Business, University of South Carolina, Columbia, SC 29201; and **Centre d'Estudis Avançats de Blanes, 17300 Blanes, Spain

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Mangroves are disappearing rapidly worldwide despite their well documented biodiversity and the ecosystem services they provide. Failure to link ecological processes and their societal benefits has favored highly destructive aquaculture and tourism developments that threaten mangroves and result in costly "externalities." Specifically, the potentially irreparable damage to fisheries because of mangrove loss has been belittled and is greatly underestimated. Here, we show that, in the Gulf of California, fisheries landings are positively related to the local abundance of mangroves and, in particular, to the productive area in the mangrove–water fringe that is used as nursery and/or feeding grounds by many commercial species. Mangrove-related fish and crab species account for 32% of the small-scale fisheries landings in the region. The annual economic median value of these fisheries is US $37,500 per hectare of mangrove fringe, falling within the higher end of values previously calculated worldwide for all mangrove services together. The ten-year discounted value of one hectare of fringe is >300 times the official cost set by the Mexican government. The destruction of mangroves has a strong economic impact on local fishing communities and on food production in the region. Our valuation of the services provided by mangroves may prove useful in making appropriate decisions for a more efficient and sustainable use of wetlands.

discounted values | economic benefits | ecosystem services | small-scale fisheries | *Rhizophora* fringe forest

Mangrove forests are one of the most biologically important ecosystems in the coastal areas; they contribute to energy flow between land and sea and provide vital ecosystem services, including waste processing, habitat, food production, and recreation (1–3). These coastal forests also strongly influence the structure of neighboring marine communities by increasing the biomass of commercially important fish and invertebrates that spend part of their life cycles in the mangrove environment (4–7). The value of mangrove ecosystem services worldwide has been estimated as an annual global flow of US$ 1,648 billion (8). Nevertheless, mangroves continue to disappear at an alarming rate because of increased coastal development, tourism, and aquaculture (9–13). This ongoing loss reflects the failure of conservation, fisheries and social scientists, and economists (14, 15) to incorporate ecosystem-based management in public policy. Moreover, evidence linking ecological processes and economic benefits has been scarce (16), and market-oriented strategies for conservation have led to a greatly polarized debate about the paradigm of ecosystem services (17–20). At the same time, economists have used a suite of valuation techniques that have undervalued ecosystem services because of insufficient data and questionable assumptions (21).

The Gulf of California is the northernmost limit for the distribution of mangroves in the Eastern Pacific. On the western coast of the Gulf of California, mangroves are distributed from the Cape region to the center of the Baja California peninsula, mostly in small bays, estuaries, and isolated mangrove pockets (22, 23). On the eastern side of the gulf, mangrove forests are distributed from Tiburón Island in Sonora, south to Sinaloa and Nayarit, in large coastal lagoons that show extensive mangrove coverage. On the Pacific side of the peninsula, the largest mangrove forests are found inside the coastal lagoons of Magdalena Bay (Fig. 1). Although human density is low in the Gulf of California, there is an increasing pressure to transform mangroves into shrimp farms and tourism developments (24–26). Additionally, modification of water flows through construction of marinas and channels is also an important threat for these ecosystems; for example, coastal areas near La Paz alone lost 23% of the mangrove forests between 1973 and 1981 because of development (27). Today, mangroves are disappearing at a regional rate of 2% annually because of sedimentation, eutrophication, and deforestation (28).

Despite the importance of mangrove forests for food production and economic benefits to local human communities, the potentially irreparable damage to fisheries because of mangrove loss has not been estimated in detail. To test the hypothesis that the amount of mangrove forests has a direct bearing on the production of many commercially important fisheries, in this study we examine the size of fisheries landings in 13 coastal segments of Baja California and the Gulf of California and compare them with the extent of mangrove forests within those same segments. Fisheries data included 9,146 landing records registered between 2001 and 2005 in 25 local offices of the Mexican National Fisheries and Aquaculture Commission (CONAPESCA) in the coastal states of Baja California Sur, Sonora, Sinaloa, and Nayarit (Fig. 1). The majority of the landings recorded in each office came from local fishing grounds that typically include mangrove areas, offshore reefs, or sandy bottoms nearby. Comparable data for the area of mangroves within the same 13 coastal regions were obtained from a wetland database for northern Mexico (29, 30).

Results

Fisheries landings increased positively with total mangrove area ($r^2 = 0.70$, $P = 0.0002$), but the scaling analysis indicated that a significantly better fit could be obtained if the square root of the mangrove area was used as the predictor of landings ($r^2 = 0.76$, $P = 0.00004$; Fig. 2). The square root of the mangrove area, in turn, was directly related to the length of the mangrove fringe by a simple equivalence relationship that was unrelated to mangrove size or location [fringe = square root of area $\times$ 6.13 ($\pm$0.45 SE)]. That is, the fisheries we analyzed only use mangroves as

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‡To whom correspondence should be addressed. E-mail: maburto@ucsd.edu.

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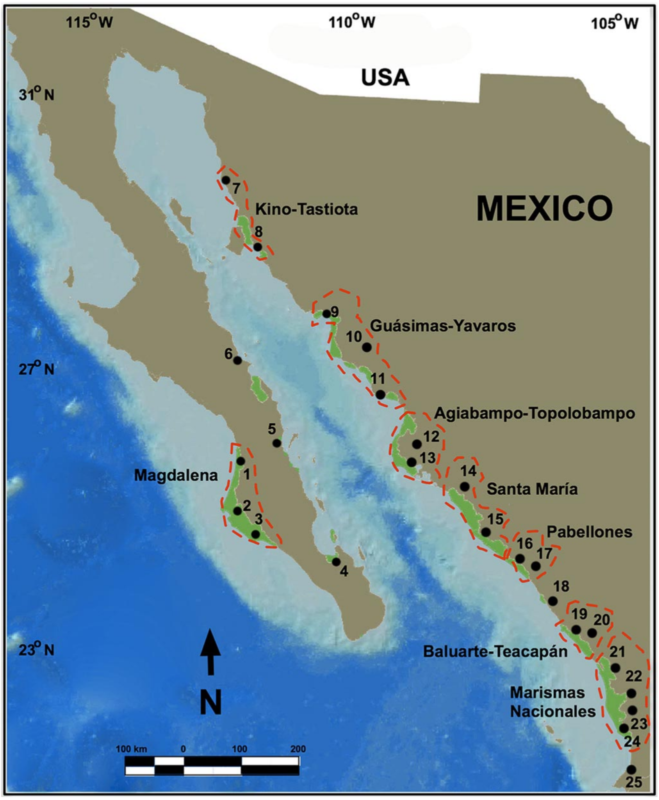

Fig. 1. The Gulf of California and the 13 fishing regions (red dashed perimeters) considered in this study, based on mangrove distribution and affinity in the composition of landings. These regions represent physical hydrogeomorphic landscape units, distinctive from adjacent landscapes. Green areas represent mangroves; black dots indicate the location of the local offices of the Mexican National Fisheries and Aquaculture Commission (CONAPESCA).

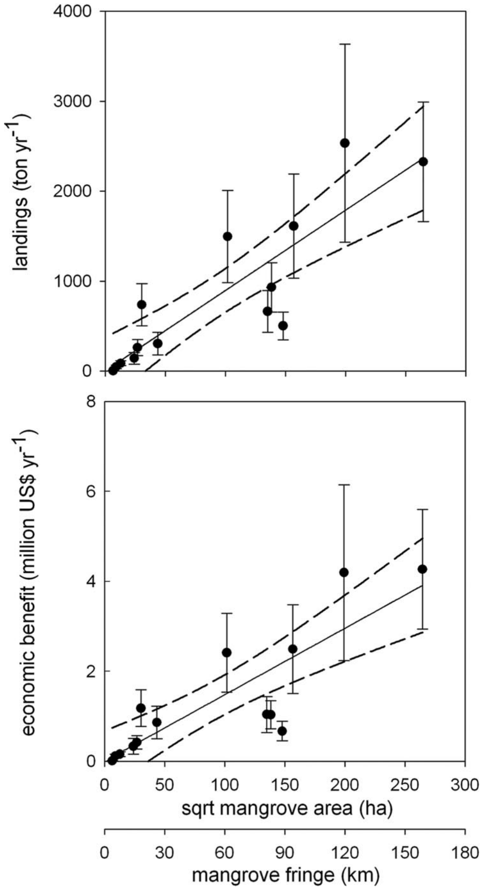

Fig. 2. Relationship between landings (fish and blue crab) and economic value (price paid to fishermen by local fishing cooperatives) against the area of mangrove fringe in the Gulf of California. Data are average ± SE (2001–2005; solid line, model; dashed line, 95% confidence intervals.

linear, one-dimensional habitat, a pattern that reflects the well known use of the edge of mangroves as nursery or feeding grounds by many marine species (31, 32). This linear trend was maintained for fish and blue crab in all years analyzed. To discard other alternative explanations, we tested for other environmental variables (estuary size, sea-grass beds, latitude, local rainfall, and fishing effort) and found that fisheries landings were not significantly related to any of them (supporting information (SI) Table S1).

The yearly landings between 2001 and 2005 for fish and blue crab in the Gulf of California averaged 11,600 tons. This production generated an average annual income of US$ 19 million for fishermen in the 13 fishing regions. The species composition of the local landings varied across the regions and this variation, in turn, influenced the total value of landings. Areas with smaller mangrove ecosystems, mostly located in the Baja California peninsula, showed more landings of high-priced resources like snappers and snooks.

The annual value of the services provided to the fishery by mangroves per kilometer of fringe averaged US$ 25,149 (±1,395 SE) km^{-1}. The mangrove fringes, normally occupied by red mangrove (*Rhizophora mangle*), have a width of ≈5–10 m and are replaced further inland by a mudflat forest dominated by black mangrove *Avicennia germinans*. Thus, one kilometer of mangrove fringe contains 0.5–1.0 hectare (ha) of suitable habitat for marine organisms, and, on a per hectare basis, the annual productivity of the mangrove fringe alone is approximately US$ 25,000 to US$ 50,000 with a median value of US$ 37,500.

Our estimates of the economic production (US$·$ha^{-1}$·$yr^{-1}$) for the areas located along the productive mangrove fringe are within the higher end of earlier assessments (7, 8, 33; Table 1). More importantly, the present discounted values (using a 5%

Table 1. Estimated mangrove ecosystem service values worldwide

Source	Region	Ecosystem services included	Value, US$·$ha^{-1}$·$yr^{-1}$
Constanza *et al.* (8)	Worldwide	All services*	9,900
Sathirathai and Barbier (33)	Thailand	All services*	27,264–35,921
Rönnbäck (7)	Worldwide	All fisheries	750–11,280
This study (fringe mangrove)	México	Fish and blue crab fisheries	37,500

*Disturbance regulation, waste treatment, habitat/refugia, food production, raw materials, and recreation.

ENVIRONMENTAL SCIENCES

Table 2. Cost estimations of transforming mangrove ecosystems in the Gulf of California

Time horizon, years	US$·ha^{-1} of fringe mangrove, present discounted values*
4	139,622
6	199,855
10	304,043
30	605,290
50	718,827
100	781,511

*Per-hectare land value by using a 5% annual discount rate, based exclusively on the long-term contribution of mangroves to regional production of fish and blue crab.

discount rate) of these flows for a hectare of mangrove fringe maintained in productive conditions during a given number of years provide a striking contrast with preceding values set in the region. For instance, over 30 years, the transformation of one hectare of mangrove fringe would cost local economies approximately US$ 605,290 (Table 2).

Discussion

Other authors have also found a square-root relationship between mangrove area and fisheries (34), or have stressed the importance of mangrove fringes in the health of coastal ecosystems (35). Our study provides results with implications for public policies designed to regulate the use of coastal resources. First, mangroves in the Gulf of California produce an important amount of food each year. For fish alone, 31.7% of the small-scale fishery landings from 2001 to 2005 comprised species related to mangrove forests. Second, our estimates represent only a lower bound because we considered exclusively the local benefits generated by fish and blue crab without taking into account indirect or existence values (36). Third, although we considered other explanatory environmental variables for fisheries landings, the analysis showed that only the mangrove area is significantly related to the amount of landings produced every year. Finally, in the Mexican government administration time frame (6 years), the fisheries-based long-term value of one hectare of fringe mangrove is 200 times higher than the standard value of US$ 1,020 ha^{-1} established by the Mexican National Forest Commission (37).

Our analysis is based on data for a single time period, and changes in the price of fish and blue crab, or in the harvestable volume of the fisheries, can potentially modify our results. However, considering the price elasticity of demand for fish protein in Mexico (38) and the country's annual population growth of >1%, it seems unlikely that demand for fish will decline significantly in the future. Furthermore, with >60% of the world's fisheries declining (39), it also seems unlikely that there will be dramatic increases in the supply of fish in the near future. Thus, significant decreases in the future value of the fishery services provided by mangroves are improbable.

Our study was done by using a wide-ranging compilation of fisheries landings, data frequently unavailable and very difficult to integrate into an interdisciplinary valuation framework. Additionally, we took advantage of the spatial variation in the amount of mangrove habitat between different fishing regions to develop a more realistic production function of fisheries related with mangroves. These arguments distinguish our economic valuation approach from previous assessments (7, 8, 33), and support the higher value found for a hectare of mangrove just for fisheries alone. Our results highlight the economic benefits of mangrove services to Mexico's economy.

The extreme undervaluation of the benefits generated by mangroves for fisheries versus the projected benefits of coastal development and aquaculture reveals a management crisis for coastal areas in the Gulf of California. Current agendas pursued by the different economic sectors have been developed independently, resulting in little, if any, compatibility between individual goals, and the undervaluation of ecosystem services in current decision-making processes exacerbates environmental degradation. The precarious state of coastal wetlands in Northwestern Mexico and in the world in general cannot be ignored, in particular, in an age (40) where food production has important implications for human welfare.

Materials and Methods

We worked with landing records provided by the National Fisheries Commission (CONAPESCA). Although these records are publicly available by request in any local office in each state's municipalities, data are compiled in CONAPESCA headquarters (Mazatlan, Sinaloa, México), where we obtained a database containing 54,679 records, including monthly crustacean and fish landings. Landings were reported from 2001 to 2005 in 41 offices located along the coasts of the five states surrounding the Gulf of California (Baja California, Baja California Sur, Sonora, Sinaloa, and Nayarit). We only considered data from (Tables S1 and S2): (*i*) the 25 fisheries offices that have mangrove ecosystems within a 50-km range [small-scale fishing *pangas*, motored fiberglass skiffs equipped mostly with hand lines and gillnets usually operate within 50 km from their home port (41)]; and (*ii*) biological groups related to mangroves in any part of their life cycle, such as blue crab, grunts, snappers, snooks, *mojarra*, mullets, and marine catfishes. Data from different offices within the same coastal lagoons were lumped together as part of one single fishing region or corridor, totaling 13 fishing regions (Fig. 1).

We used scaling models to explore how the relationship between mangrove area and fisheries changes as the size of the mangrove habitat increases. Scaling relationships describe how patch-related resource productivity varies with patch size. Ecotonal species that only explore the edge of patches will use their environment as a linear, one-dimensional habitat; as the area of the patch grows, the population numbers will also increase as a function of the square root of the area—a measure of the patch's edge. Conversely, species that use the entire patch area will explore and use their environment fully as a two-dimensional habitat, and their productivity will scale-up linearly with patch area. Thus, the slope of a power function between productivity and patch area plotted on a log-log scale can be used to test hypotheses about the way the resource populations use the environment: if the slope approaches 0.5, then the organisms are mostly using the patch edges; however if the slope approaches unity, the resource species are using the patches in their entirety.

The geographic information used for this study was obtained from an extensive inventory of Mexican wetlands (Table S1), which includes cover data estimated from Landsat Thematic Mapper (TM) satellite images. In particular, we used cover data on (*i*) mangrove ecosystems (areas dominated by *R. mangle*, *Laguncularia racemosa*, *A. germinans*, and *Conocarpus erectus*), (*ii*) estuarine systems (deep and shallow waters inside the coastal lagoons), and (*iii*) submerged aquatic vegetation (deep and shallow waters dominated by bottom-rooted sea-grasses such as *Ruppia maritima*, *Halodule wrightii*, *Syringodium filiformis*, *Zostera marina*, and *Thalassia testudinum*). These three variables can influence the productivity of fish and invertebrates because they represent feeding and nursery habitats.

Because of its large scale, the inventory cited above lacked information on small mangrove wetlands close to four CONAPESCA offices (La Paz, Loreto, Santa Rosalia, and Peñita de Jaltemba). These represent only 0.74% of the mangrove areas considered in this study. It is extremely difficult to work with these isolated mangrove pockets (mean, 14.1 ha ± 2.5 SE) by using satellite images, because the color band of many areas with dense vegetation, predominantly palms or coastal mesquite thickets, could be erroneously confounded with mangrove forests and give an incorrect overestimation of mangrove cover. To solve this problem, we carried out field trips in 2005 and 2006 to survey all mangrove patches distributed in small bays and islands. By using small boats we were able to navigate inside the lagoons and hike in the inland parts of the forests, to take geographic bearings of the extent of mangrove trees. Our field data and observations were used as ground-truthing data points to map the patches as polygons by using Google Earth software. These polygons were saved as KML files (a file format used to display geographic data in an Earth browser such as Google Earth, and that uses a tag-based structure with nested elements and attributes similar to the XML standard), to obtain the total area of the mapped mangrove patches within a 50-km range from each office, by using GE Path software (www.sgrillo.net).

To test for alternative hypotheses other than mangrove area explaining variation in landings, we also regressed other potentially explanatory variables such as the area of sea-grass beds and lagoon estuaries, regional climatic variables such as local precipitation, and fishing effort expressed as the number of boats per fishing region (Table S1). Partial regression coefficients were computed to verify the significance of each variable, and tested by using a two-tailed Student's *t* test.

Finally, to estimate the services provided by mangroves to the local communities, all landings were converted to economic values by using the prices paid locally to the fishermen by fishing cooperatives (the ex-vessel revenue), ignoring all nonfishery benefits of mangroves such as existence and biodiversity values. To remain conservative in our estimates of mangrove value, we also ignored consumer surplus. To get an estimate of the economic worth of mangroves from the point of view of fisheries, the present discounted values of future annual revenues were accumulated for different time spans, ranging from 4 to 100 years, and by using a 5% discount rate.

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