ENVIRONMENTAL STUDIES

A natural experiment reveals the impact of hydroelectric dams on the estuaries of tropical rivers

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We tested how sediment trapping by hydroelectric dams affects tropical estuaries by comparing two dammed and two undammed rivers on Mexico's Pacific coast. We found that dams demonstrably affected the stability and productivity of the estuaries. The two rivers dammed for hydroelectricity had a rapid coastal recession (between 7.9 and 21.5 ha year^{-1}) in what should otherwise be an accretional coastline. The economic consequences of this dam-induced coastal erosion include loss of habitat for fisheries, loss of coastal protection, release of carbon sequestered in coastal sediments, loss of biodiversity, and the decline of estuarine livelihoods. We estimate that the cost of the environmental damages a dam can cause in the lower part of basin almost doubles the purported benefits of emission reductions from hydroelectric generation.

INTRODUCTION

During the last decades, many voices have expressed concern about the environmental impact of large dams. Although hydroelectric power is renewable and can reduce CO_2 emissions derived from the burning of fossil fuels for the generation of thermoelectricity, large hydroelectric dams may also have important adverse consequences on the environment because they alter river hydrology, nutrients concentration and amounts, and the lifecycles of species that depend on freshwater habitats. Reductions in water pulses downstream can increase substrate salinity, lower the groundwater table, and make water unusable for drinking and irrigation (1). Decomposition of organic matter drowned in the dam's reservoir can emit large amounts of methane and can also promote the leaching of toxic metals from the flooded minerals and rocks in the reservoir (1). Sediments that are crucial for natural cycles are trapped in the dam's reservoir affecting the normal functioning of downstream ecosystems, including wetlands and coastal lagoons (1). Thirty-three of the largest deltas in the world are now rapidly receding and sinking, with serious consequences for regional agriculture and livelihoods [see (2) and references therein]. Although alterations of the water flow by damming and diversions are not the only cause of deltaic degradation (aquifer water extraction and oil drilling, for example, seem to be playing a role too), they are the most important common cause globally.

While in many developed nations strong public opinion has gradually developed against dams and the era of big dam building is considered to be over [e.g., (3)], many developing countries still see the construction of dams as a strong incentive for development, capable of mobilizing investment, activating the demand for industrial supplies such as steel and concrete, offering employment, and providing renewable energy. However, the environmental costs in terms of loss of land, alterations to the water regime, habitat disruption for riverine species, sediment trapping in the reservoir, and the degradation of water quality are often not weighed appropriately against the purported benefits. Strong debates persist around this issue throughout the developing world, and many studies [e.g., (4–7)] have tried to tackle the complex issue of economic tradeoffs between hydropower generation and the associated environmental impacts in an attempt to achieve a goal of generating electricity while at the same time avoiding many of the environmental costs of large dams.

Tropical rivers normally carry large amounts of suspended sediments that feed sandbars, deltas, and accretional coastlines. Most of these sediments become trapped in the body of large reservoirs, changing the coastal dynamics in the estuaries of dammed rivers. The impact of large dams in coastlines, estuaries, deltas, and lagoons is commonly understudied in the environmental studies of hydroelectric projects. Furthermore, when evaluated, it has historically been approached by analyzing time series documenting the state of the estuary and the lower basin before and after the damming of the river. This approach, however, is based on repeated observations along the same river and not based on true statistical replicates. Long-term change can be the result of many other factors that have varied with time and not necessarily of the dam itself. A comparative study between dammed and undammed rivers may provide critically needed evidence.

The Pacific coast of Mexico in the States of Nayarit and Sinaloa provides an ideal setting for this approach. Four rivers run roughly parallel to each other down the Sierra Madre from the Mexican Plateau and reach the Pacific coast relatively near to each other. Two of them have been dammed for hydroelectricity, while the other two still flow free into the coastal estuaries. The southernmost one, the Santiago River, harbors four dams (Aguamilpa, finished in 1994; El Cajón, 2007; La Yesca, 2012; and Santa Rosa, 1964), and the northernmost one, the Fuerte River, was dammed in 1956 by the El Mahone dam. The remaining two rivers, the San Pedro and the Acaponeta, still flow free onto the coastal plains (they both have some small impoundments for irrigation but are still largely running free). All four rivers flow into large coastal lagoon systems: Marismas Nacionales (Mexico's largest coastal wetland) and the Ahome wetlands.

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Using these rivers as a "natural experiment," we analyzed the way sediment trapping by dams affects the estuaries of tropical rivers. If the sediment reduction imposed by the operation of the dams distinctly affects the lagoon system, then significant differences in coastal dynamics should be evident when comparing the estuary of the two undammed rivers against the estuaries of the Santiago and the Fuerte rivers, which have been dammed for 23 and 61 years, respectively.

Thus, the objective of our study was to analyze the geomorphologic dynamics of the coast immediately adjacent to the estuaries of two dammed rivers and compare it with that of the region's two nondammed rivers, describing the differences between the two systems. We also calculated the impact of sediment reduction in terms of the loss of ecosystem services and emissions of carbon into the atmosphere. Last, we present a balance between the benefits and costs of damming a tropical river for energy production against the alternative of letting the river flow free into the ocean.

The study area

All four rivers descend from the Mexican highlands across the Sierra Madre into the wetlands of the Pacific coast of Mexico. Three of them, Santiago, San Pedro, and Acaponeta, reach the coast at Marismas Nacionales, the largest (ca. 1800 km^2) tropical lagoon complex in the Pacific coasts of the American continent. The fourth and northernmost river, Río Fuerte, reaches the coast in the more northern Ahome wetlands in the Gulf of California (table S1).

The Fuerte River was dammed for hydroelectricity in 1956 by the El Mahone dam and the Santiago River in 1994 by the Aguamilpa dam. Other dams have been built since in both rivers upstream of these lower-basin reservoirs. Currently, only 4% of the area of the Fuerte and 2% of the Santiago watersheds are free of dams and can produce unobstructed runoff feeding the lower basin and reaching the ocean at Punta Ahome (25°57′09″N, 109°26′37″W) and Boca del Asadero (21°38′05″N, 105°26′44″W), respectively. Most (>95%) of the flow in these two rivers goes through reservoirs where a large part of their sediments are trapped.

The other two rivers, Acaponeta and San Pedro, do not have dams in their lower basin and are largely "free" rivers. Both come down across the Sierra Madre from the highlands of Durango; the Acaponeta reaches the Agua Brava Lagoon in the heart of the Marismas Nacionales wetlands from where it drains into the Pacific Ocean through an estuary known as Boca de Teacapán (22°32′05″N, 105°45′15″W). The San Pedro reaches the wetlands at the Mezcaltitán lagoon from where it drains into the ocean at Boca de Camichín (21°43′58″N, 105°29′32′′W). The Acaponeta has no dams along its course, although some of its water is diverted, mostly during the dry season, for local irrigation. The San Pedro has two dams in its upper watershed, which are used for irrigation in the highlands of Durango, but most (ca. 75%) of its watershed drains unobstructed into the sea. Detailed information on the four rivers is provided as Supplementary Materials.

Marismas Nacionales

Marismas Nacionales (National Marshlands) is a large, complex lagoon system that runs parallel to the coast for some 150 km in the States of Nayarit and Sinaloa from the historic port of San Blas in the south to the village of Escuinapa in the north. One of its most distinctive traits is the presence of two well-defined geomorphologic units: A system of large inner lagoons surrounded by mangrove forests and a coastal system of parallel beach ridges that forms a

spectacular succession of accretion lines separating the lagoons from the coast of the Pacific Ocean (Fig. 1). The coastal ridges of Marismas Nacionales have been studied in great detail since the 1960s by Curray et al. (8–10). The ridges are formed by coastal accretion derived from the continental input of sediments brought down from the Sierra Madre into the coastal plains by three main rivers: Acaponeta, San Pedro, and Santiago. After post-Pleistocene sea-level rise stabilized, ca. 5000 years before the present, the ridges started to form at a mean rate of approximately 1 m every 12 years. The ridges are made up of a mixture of sediments derived from the longshore transportation of the Santiago and San Pedro rivers and the onshore transportation of reworked sediment from the now drowned paleo-river delta constructed on the continental shelf during the previous sea-level low stand in the Pleistocene and early Holocene (11). The current boundary between the large inner lagoons and the ridge system marks the ancient coastline from where the ridges grew. Curray's seminal studies allow calculating the rate at which the Marismas coastline expanded and grew into the ocean shelf, as well as the amount of sediment brought in the past by the rivers that gave origin to this unique system. The dynamics of sediment deposition along the coastline, and particularly of the coastal ridge systems, is at the core of current concerns about the environmental impact of hydroelectric dams. Reductions in sediment loads from sediment trapping in reservoirs may reverse the historic
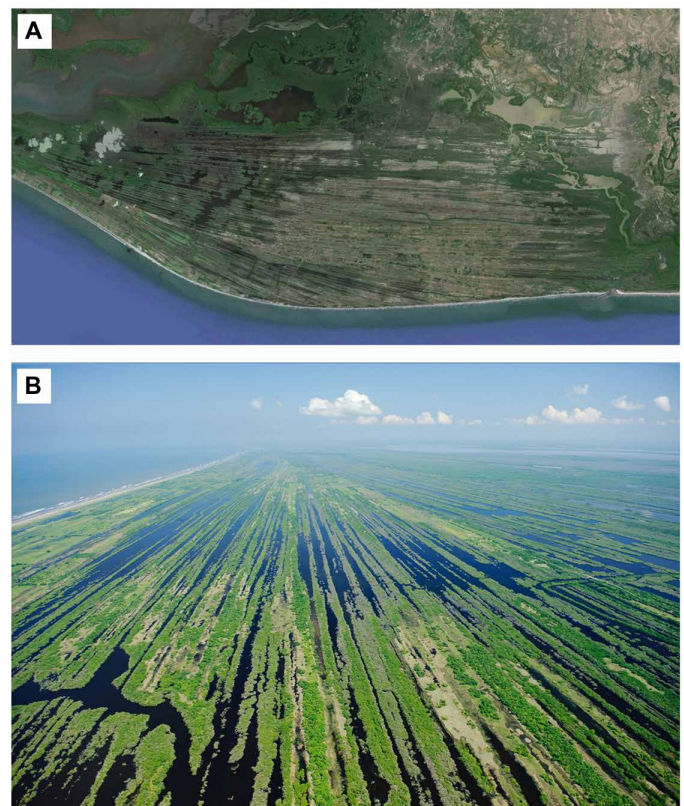

Fig. 1. The Marismas Nacionales lagoon system. (**A**) Satellite image of Marismas Nacionales showing the inland system of Pleistocene and early Holocene lagoons and the coastal system of late Holocene beach ridges separating the lagoons from the sea (photo credit: Google Earth). (**B**) Aerial view of the parallel beach ridges derived from successive events of coastal accretion (photo credit: J. Rojo, iLCP).

accretion of the lagoon systems, opening the way to the erosion of sandbars and coastal ridges and, potentially, to the destruction of the coastal wetland ecosystems.

RESULTS

Striking differences in the coastal dynamics of the four river systems were found between the four rivers in their coastal dynamics as evaluated through an analysis of both Landsat and Google Earth images, encompassing both decadal and shorter-term time scales.

Multidecadal coastal dynamics

The coast around the estuary of the Fuerte River, dammed in 1956, receded during the two study periods, losing on average 7.9 ha year^{-1} during 1975–1990 and 11.5 ha year^{-1} during 1990–2010 (Fig. 2). The coast around the estuary of the Santiago River, first dammed in 1994, grew between 1975 and 1990 at a mean rate of 4.5 ha year^{-1}, before the first dam was built, but started to rapidly recede during

the 1990–2010 period at a rate of 21.5 ha year^{-1} (Fig. 3A). In contrast, the coast around the Acaponeta River stayed largely stable, gaining on average 0.2 ha year^{-1} during 1975–1990 and losing 0.4 ha year^{-1} during 1990–2010. Last, the coast of the San Pedro River showed fast accretion rates during both periods, gaining 7.4 ha year^{-1} during 1975–1990 and 5.2 ha year^{-1} during 1990–2010.

Recent coastal dynamics

An analysis of the Google Earth images for the 2003–2015 interval confirmed the general Landsat trends (Fig. 4): During the last decade, the coastline in the sandbar of the Santiago River retreated at a rate of −48.5 m year^{-1}, while the sandbar of the San Pedro River grew at a rate of 2.8 m year^{-1}, the Acaponeta River stayed largely stable at a rate of −0.3 m year^{-1}, and the Fuerte River retreated at a rate of −14.3 m year^{-1} (Fig. 3B). Comparing the mean rates by means of a t test, we found that the rate in the Acaponeta River did not differ significantly from zero ($P = 0.31$), while the sandbar of the San Pedro River is significantly advancing ($P = 0.0002$), and those of
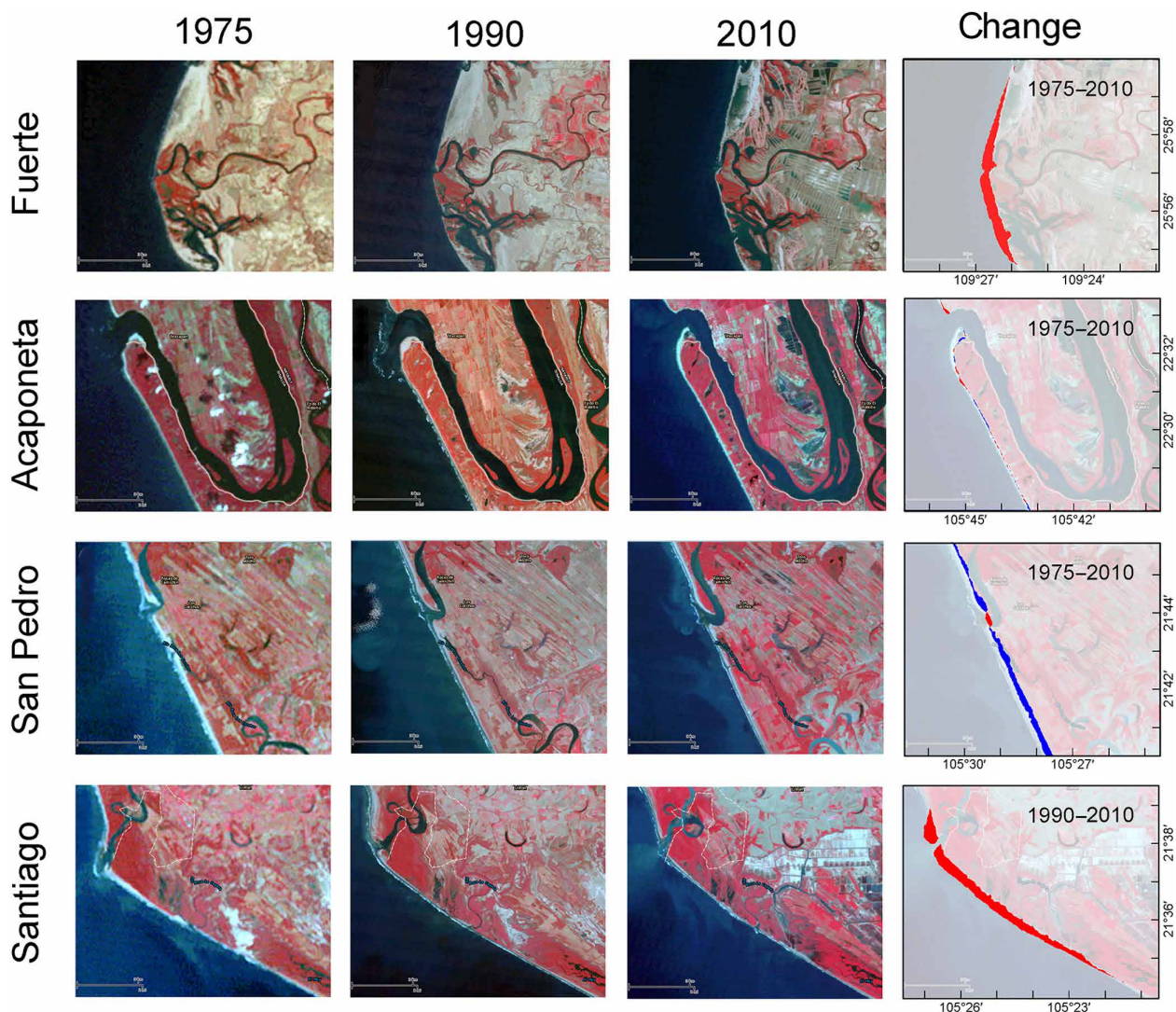

Fig. 2. Multidecadal coastal change. Landsat images of the coast adjacent to the estuaries of the Fuerte, Acaponeta, San Pedro, and Santiago rivers for years 1975, 1990, and 2010 (photo credit: changematters.esri.com/compare). The images at the right show changes in the coastline during the periods indicated in the figures; blue color indicates coastal accretion, and red indicates coastal erosion.
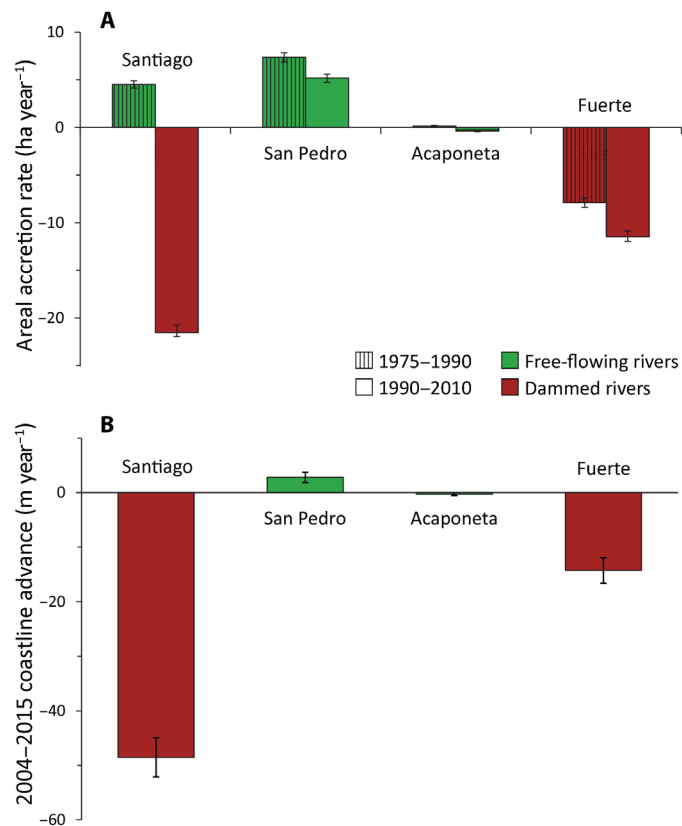
Fig. 3. Coastal accretion rates. (**A**) Areal accretion or erosion rates (ha year⁻¹) for the Santiago, San Pedro, Acaponeta, and Fuerte coastlines for the 1975–1990 period (hatched bars) and the 1990–2010 period (open bars) derived from Landsat images. Free-flowing rivers are coded in green, and dammed rivers are in red (note that the Santiago River was free flowing in the 1975–1990 period and dammed in 1990–2010 period). (**B**) Linear advance or retreat rates (m year⁻¹) during the 2003–2015 period derived from Google Earth images for the Santiago, San Pedro, Acaponeta, and Fuerte sandbars (see Fig. 4 for details on the image dates). Free rivers are coded in green, and dammed rivers are in red.

the Santiago and Fuerte rivers are significantly retreating ($P < 0.0001$ and $P = 0.015$, respectively).

Ground surveys
The vegetation surveys confirmed the trends observed in the satellite images (Fig. 5): The two nondammed rivers (San Pedro and Acaponeta) showed defined successional accreting coasts along their sandbars, with pioneer species in the seaward front, followed by fixed dune perennials such as coastal mesquite (*Prosopis juliflora*), then by a mature tropical dry forest, and lastly by an inland lagoon mangrove forest with black mangrove (*Avicennia germinans*) in the mudflats and red mangrove (*Rhizophora mangle*) along the lagoon fringe. The two dammed rivers (Santiago and Fuerte) showed signs of intense erosion along their seaward fringe, with the accretional sandbars gone, inland lagoon mangrove forests being exposed directly to the erosive action of the waves, and dense masses of dead trunks and stumps being washed into the sea. The diversity of terrestrial vegetation in the sandbars of the four rivers differed drastically. While in the sandbars of the San Pedro and the Acaponeta we identified 33 and 26 different species of terrestrial plants, respectively, we counted eight and four species only in the Fuerte and the

Santiago sandbars. Overall, these species richness values differ significantly ($\chi^2 = 32.9$, df = 3; $P < 0.0001$): The two nondammed rivers shelter significantly higher species richness than the dammed rivers, and the richness of the four sandbars is positively correlated with the rate of coastal accretion and erosion (Fig. 6A). Furthermore, many of the species present in the coastal dunes and tropical dry forests of the first two rivers are regional or local endemics of high conservation value (see Supplementary Materials).

Impact on fisheries
The number of boats operating in each estuary was also positively correlated with the rate of coastal accretion (Fig. 6B), linearly decreasing from 163 boats in the San Pedro estuary with the highest accretion rate to 47 boats in the Santiago estuary with the highest erosional rate. These findings were consistent with the 2006 boat survey in the whole floodplain wetlands of each river: In the 2006 counts, the entire lower basins of the San Pedro and the Acaponeta rivers had, on average, 1083 and 396 fishing boats, respectively, while the Fuerte and the Santiago rivers only harbored 19 and 47 boats, respectively (Fig. 6C). The difference in the number of fishing boats is mirrored in total landings: According to fisheries data presented in the environmental impact statement (EIA) (*12*), the San Pedro River (Camichín, 634 ha) yielded in the 2007–2008 fishing season 658 tons of shrimp, oysters, and fish, while the concession in the mouth of the Santiago River (Villa Juárez, 3146 ha) yielded only 35 tons in the same period. The same study reports that, as a whole, the pooled concessions in the wetland plains of the San Pedro River (78,157 ha) yielded in 2007–2008 a total of 2352 tons of fisheries.

DISCUSSION
Our analyses show that the damming of tropical rivers, with the subsequent reduction of sediment load reaching the coasts, has highly destructive effects on the stability and productivity of the coastline and lower estuaries. The two rivers dammed for hydroelectricity in their lower basin are experiencing rapid coastal recession in what should otherwise be an accretional coastline. Over 1 million tons of sediment are trapped in the dams along the Fuerte and Santiago rivers every year (see section S2 for details), and as a result, the coastline around the estuary of the Santiago River is losing more than 20 ha of coastal tropical forests and mangroves every year. The coastline around the estuary of the Fuerte River, which was dammed over half a century ago, is still receding rapidly losing every year approximately 10 ha of mangrove forests, now exposed to the direct erosive action of the waves. The economic consequences of this destructive coastal erosion induced by the damming of the rivers are multiple.

Loss of open sea fisheries services
It has been shown that mangroves in general (and fringe red mangrove forests in particular) provide critical habitat and food for the growth and survival of many important open sea fisheries during their juvenile stages (*13*). On the basis of their contribution to fisheries, the value of fringe mangroves in the Gulf of California has been estimated at approximately 650,000 US$/ha. If we assume, based on our field sampling, that of the total area of forests lost every year near the mouth of the Santiago River, some 2 ha (ca. 10%) correspond to fringe red mangroves, then it follows that approximately US$ 1.3 million are lost every year from Mexico's natural capital in fishery services. The estimation of the fishing effort in the Gulf of
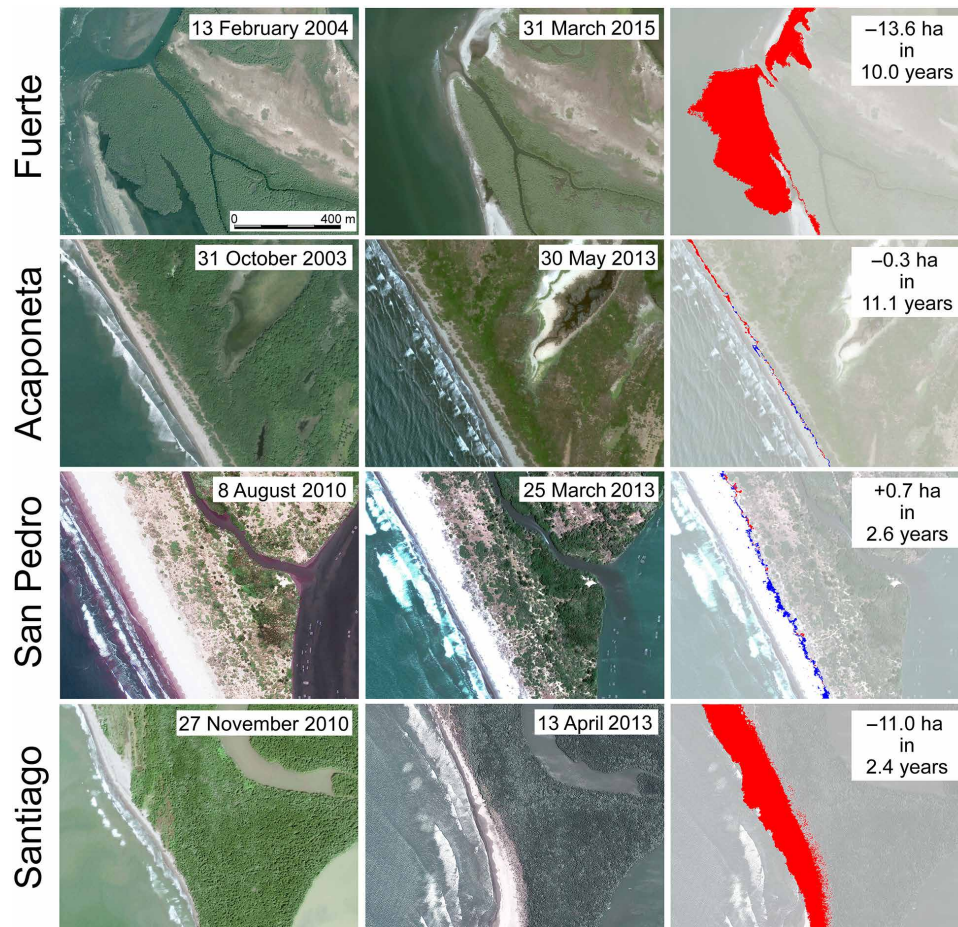
Fig. 4. Short-term coastal change. Comparative historic images of the sandbars adjacent to the mouths of the Fuerte, Acaponeta, San Pedro, and Santiago rivers for the dates indicated in the image (photo credit: Google Earth). The images at the right show changes in the coastline during the two periods: blue indicates coastal accretion, and red indicates coastal erosion.

California suggests that the fishing effort is highest close to highly populated human settlements on the coast and/or fishing camps where the number of fishing vessels is high (*14*). The river mouths analyzed in this research are located along the eastern side of the Gulf of California, where the highest fishing effort values were estimated. Although El Fuerte river mouth is located between Guaymas (in the north) and Mazatlán (in the south) along the most populated coastline in the region, the fishing effort is significantly less than the fishing effort in the San Pedro Mezquital river mouth, supporting our results that the degradation of the estuarine ecosystems by dam impacts have significant negative effects in the fishing sector independently of the distribution of the fishing effort in the region.

Loss of coastal protection and other mangrove services
Apart from their role as providers of habitat for fisheries, mangroves and accretional sandbars provide a whole set of additional services including coastal protection from hurricanes and tropical storms, wildlife conservation services, and recreational habitat. On the basis of the provision of these services, Costanza *et al.* (*15*) valued mangrove ecosystems and coastal wetlands at 194,000 US$/ha. It follows then that the annual loss of more than 20 ha of mangrove and coastal forests observed in the coast around the Santiago River represents an annual loss of US$ 3.9 million from Mexico's natural capital

based on the provision of other environmental services different from fisheries.

Release of previously immobilized carbon
Mangrove forests are one of the most carbon-rich ecosystems on earth, harboring, on average, more than 1000 tons of belowground carbon per hectare (*16*). Mangroves at Marismas Nacionales, however, are not as rich in carbon as those in other lagoons, possibly as a result of the rapid dynamics of the coastal ridge accretional system. Our own measures have estimated some 300 tons/ha of total carbon in these forests (*17*). Thus, the annual loss of ca. 20 ha implies the release of some 6000 tons of carbon eroded into the ocean and presumably later decomposed and released to the atmosphere in the form of CO_2 or methane. Using the standard estimate of 21 US$/tons of carbon used in carbon trading valuations (*18*), it follows that ca. 130,000 US$ is lost every year into the form of de-immobilized carbon.

Loss of biodiversity services
The banding of coastal vegetation along the coastal ridges is a major factor in the observed biodiversity collapse. The dunes and dry tropical forests are much more diverse in plant species than the mangrove forests and, being the two ecosystems closest to the sea,
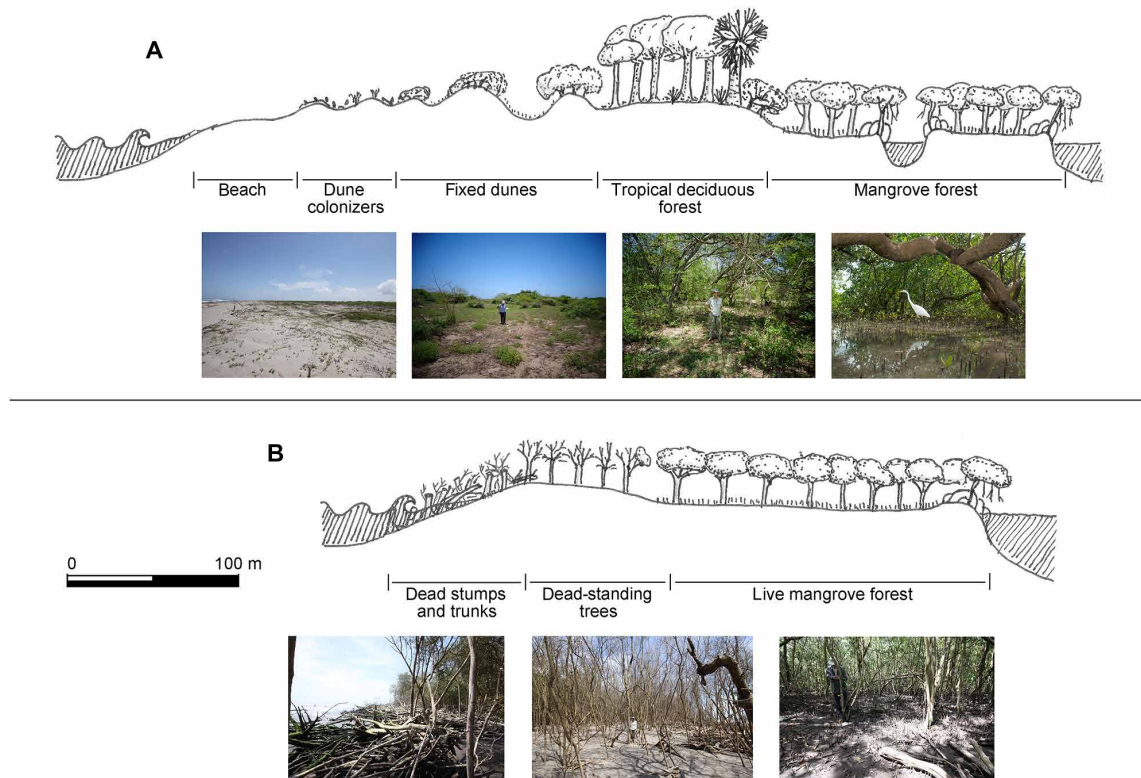
Fig. 5. Vegetation profiles. (**A**) Vegetation profile of the accretional sandbar of the San Pedro River with images of the main plant communities. (**B**) Vegetation profile of the erosional sandbar of the Santiago River with images of the receding black mangrove forest being eroded away into the advancing coastline. Photo credit: E.E., UC Riverside.

are the first to go as the coast recedes due to river damming. The tropical dry deciduous forests of the Pacific coast of Mexico rank among the most endangered ecosystems in the country (*19*). They have been put under threat by the expansion of agriculture, ranching, and urbanization. For this reason, the stretches of forest that survive in the coastal sandbars of this region play not only an important role in shoreline protection and buffering against hurricanes but also in the conservation of Mexican biodiversity and wildlife habitat.

Degradation of estuarine livelihoods

It is a well-established fact that catadromous migration, in which some fish species migrate from the ocean to feed in river estuaries, dominates in tropical coasts where the productivity of estuarine and lagoon normally exceeds that of the ocean (*20*). This elevated productivity in tropical rivers depends chiefly on the input of nutrients brought into the estuaries by the rivers' suspended sediments (*21*). The process of estuarine fertilization by the continuous input of continental sediments explains why the number of fishing boats in the dammed rivers is only 2 to 5% of the number of boats in the free-flowing San Pedro River and why the total landings reported for the mouth of the Santiago River is only 5% in mass of those reported for the San Pedro River. In economic terms, this is very important for the region. The lower basin of the San Pedro River yields every year more than 1000 tons of shrimp, some 600 tons of oysters, and some 620 tons of different fish species that, at ex-vessel prices, generate a regional income of US$ 5.8 million distributed among 3800 fishers and for the benefit of 26,000 community members (see

section S3). All four rivers have fishing markets nearby, and the two rivers where fisheries have collapsed still show evidence of large, now abandoned, fishing camps in their estuaries, a fact that suggests that fishing was intense in these estuaries in the past. Thus, based on the comparative data of fishing boats and landings for the four rivers, it becomes clear that the damming of the Santiago and the Fuerte rivers for hydroelectricity may have reduced this regional source of income in approximately 95% or more in each estuary.

CONCLUSION

The most important environmental argument frequently brought forth in favor of hydroelectric dams is that of emission reductions. These reductions, however, are often partially offset in tropical ecosystems by the emission of methane (CH_4) and CO_2 from decomposing organic matter from the forests submerged in the reservoir but can be, and often are, calculated in environmental studies around new hydroelectric projects (*22*, *23*).

However, the damages a hydroelectric project can cause in the coast and the lower part of tropical basins, in terms of loss of mangrove services and estuarine productivity, may add a significant amount to the environmental costs of a dam and are rarely calculated. These costs should be estimated and added to the many other well-known impacts of hydroelectric dams in both the reservoir itself and in the upper and mid-basin. The building of a dam on free rivers such as the San Pedro or the Acaponeta can imperil the livelihoods of fishing and rural communities in the floodable coastal plains, a social impact that should be added to the number of villagers that
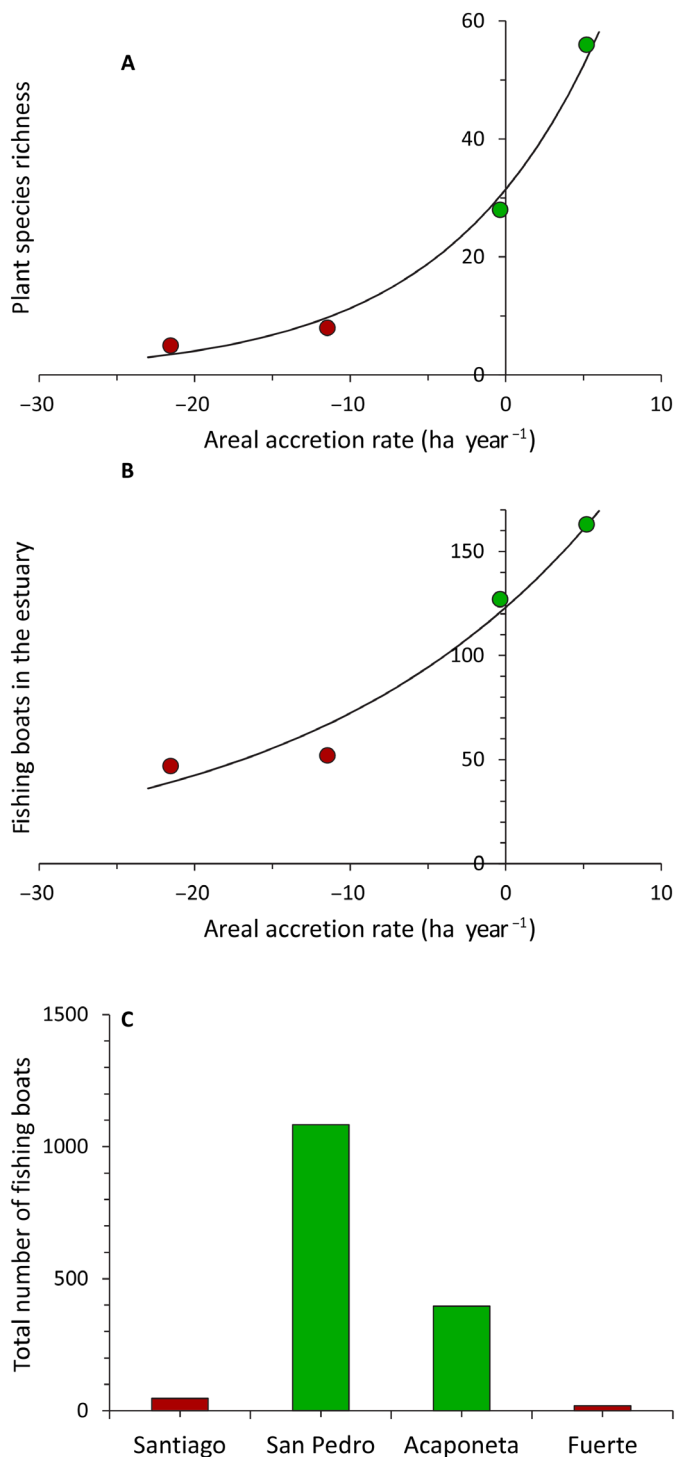
Fig. 6. Impact on vegetation and fisheries. (**A**) Log-linear relationship between the accretion rate of the coastline (negative values indicate the coast is receding) and the plant species richness of the sandbar ($r^2 = 0.98$, χ^2 deviance of the model = 67.0, df = 1; $P < 0.0001$). (**B**) Log-linear relationship between the accretion rate of the coastline and the number of boats fishing in the estuary ($r^2 = 0.95$, χ^2 deviance of the model = 97.3, df = 1; $P < 0.0001$). (**C**) Total number of fishing boats in the lower basin of each of the three rivers. The number of boats counted on the free rivers was significantly higher than the number of boats in the dammed rivers ($\chi^2 = 1907.3$, df = 3; $P < 0.0001$). In all plots, free-flowing rivers and dammed rivers are indicated by green and red markers, respectively.

often lose their land and their sacred sites under the flooded reservoir. Last, although not easily quantifiable in economic terms, large dam projects imply the loss of important coastal biodiversity and imperil the continued formation and dynamics of accretional coastal landscapes.

METHODS

Experimental design

We surveyed four of five largest rivers of the Pacific coast of Mexico: Two of them (the Fuerte and the Santiago rivers) are dammed, while the other two (the Acaponeta and the San Pedro) run free. The fifth and largest river of the Mexican Pacific coast, the Balsas River, was not surveyed because the estuary and the neighboring oceanic coasts have been walled to stop the accelerated coastal recession that started after the building of the Infiernillo dam in the lower basin. By comparing the dammed against the undammed rivers, we analyzed the way sediment trapping has affected the estuaries. We analyzed (i) long-term multidecadal change using Landsat images, (ii) short-term (<10 years) change using Google Earth Pro images, (iii) current vegetation condition through ground surveys, and (iv) estuarine productivity by counting fishing boats and using official statistics on estuarine fisheries production.

Multidecadal coastal dynamics

Using Landsat satellite images (pixel size of 30 m × 30 m) from the website changematters.com, we compared coastal sectors spanning a latitudinal range of 5.5 min (ca. 10 km of coastline), centered around the estuaries of the four rivers. For each coastal sector, we selected images for three dates: 1975 (earliest image set available), 1990, and 2010 (most recent set available). Using the color signature identifier of a digital image editor (Adobe Photoshop), we selected in each image all the pixels that corresponded to seawater and coastal unvegetated strands and simplified each image into a binary representation of terrestrial and marine pixels. We then superimposed the binary images and calculated the area of coastal vegetation that was lost or gained during the 1975–1990 and the 1990–2010 periods. Because areal calculations are derived from pixel counts, which are frequency data, we obtained standard errors for each areal estimate using the mean-to-variance properties of the Poisson distribution. To make the more recent satellite images comparable with those of 1975, we used in all cases false-color infrared imagery in which terrestrial vegetation shows up in red, and we took in all images the seaward limit of terrestrial vegetation as the boundary of terrestrial ecosystems.

Recent coastal dynamics

We used Google Earth Pro historic images of the coastal sandbars immediately adjacent to the mouth of the four rivers to compare coastal change around the estuaries of the four rivers (Santiago, November 2010–April 2013; San Pedro, August 2010–March 2013; Acaponeta, October 2003–May 2013; and Fuerte, February 2004–March 2014). The time span of these images is variable because it depends on the availability of historic imagery but is always much shorter than that of the Landsat images, encompassing in all cases less than a decade and never reaching earlier than 2004. The pixel resolution, however, is higher (1.3 m × 1.3 m for all images available for the study sites) and allows for a more detailed assessment of coastal change. In all four rivers, we selected images at the same scale,

encompassing roughly 1 km of ocean coast. Using the same procedure as with the Landsat images, we transformed each image into a binary representation of marine versus terrestrial environments, selecting in each image the marine pixels formed by ocean surface and unvegetated beach strands, and separating them from the remaining pixels, classified as terrestrial environments. By subtracting both images, we could identify areas that corresponded to terrestrial environments in the first date and had been eroded into the ocean later or, conversely, areas that were occupied by seawater or unvegetated beaches in the first image and had accreted into a vegetated terrestrial environment later. The area of lost/gained terrestrial pixels was divided by the length of the coast to obtain a linear measure of coastal advancement or retreat. Last, by numerically resampling the image with 10 random transects perpendicular to the coastline, we got an estimate of the standard error of the linear rate.

Ground surveys

We visited each of the coastal sites identified in the Google Earth images and made in each one a rapid vegetation survey to assess the status of the ecological communities and confirm or reject the hypotheses developed using the remote sensing images. The detailed methods for our vegetation survey are given as section S1. Our main goal in this ground-truthing survey was to establish whether the coastal plant communities showed the effects of accretion or recession. In accreting (growing) coasts, we expected to find a gradient with young pioneering dune plants in the seaward fringe gradually transitioning onto fixed dunes, followed by a mature coastal bar forest, and then onto the inland lagoon communities of mangroves (24). In receding (eroding) coasts, we expected to find older trees, typical of more inland communities, in the seaward fringe being exposed directly to the erosive action of the waves. The relationship between plant diversity, expressed as species richness in 1 ha of coastal sandbar, and coastal accretion/erosion rates was evaluated using log-linear regression.

Fishing activity and catches

To test whether estuarine fishing activities were affected by the large dams, we used Google Earth images to count the number of fishing boats in each estuary, up to 2 km upstream from the mouth of the river (14). In each image, we counted the total number of fishing boats that were visible, including both open-water skiffs (known as pangas) and river canoes (cayucos). The relationship between coastal accretion/erosion rates and the number of fishing boats was also evaluated using log-linear regression. We also obtained from a database developed by the World Wildlife Fund's Mexico Program (25) a detailed tally of all the boats visible in the lower river plains for the four rivers, counted by analyzing Google Earth images in spring and fall (May and December) of year 2006. To get an estimate of year-long fishing pressure in each basin, we averaged the May and December counts. Last, we obtained fisheries data from the EIA of the Las Cruces Hydroelectric Project (12) (i) to compare fisheries landings in the estuaries of the San Pedro and the Santiago rivers and (ii) to estimate the total landings that local fishers obtain from the lower San Pedro plains in the entire Marismas Nacionales wetlands.

Statistical analysis

All statistical analyses were done using the R package (26). Patterns in frequency counts (such as species numbers) were analyzed using log-linear models and chi-square tests. All other analyses were done using simple linear models and analyses of variance (ANOVAs).

SUPPLEMENTARY MATERIALS

REFERENCES AND NOTES

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Science Advances

A natural experiment reveals the impact of hydroelectric dams on the estuaries of tropical rivers

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