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# Oceanographic anomalies and sea-level rise drive mangroves inland in the Pacific coast of Mexico

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**Keywords**
Bahia Magdalena; Baja California; Coastal lagoons; Coastal vegetation change; El Niño; Sea-level rise

**Abbreviations**
ENSO, El Niño Southern Oscillation; MEI, Multivariate ENSO Index

**Nomenclature**
The International Plant Names Index (2008). Available at http://www.ipni.org

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## Abstract

**Question:** Although mangrove forests are generally regarded as highly threatened, some studies have shown that mangrove canopies in the Pacific coast of Mexico have been increasing in recent decades. We investigated the possible causes driving this reported mangrove expansion.

**Location:** The mangrove lagoons of Magdalena Bay in Baja California, Mexico.

**Methods:** We used 50-year-old aerial photographs and 24-year-old satellite images to compare long-term vegetation change, surveyed a coastal vegetation transect to analyse flooding levels, compiled six decades of tidal and oceanographic information, as well as hurricane data to analyse changes in storm frequency or sea-level conditions, and used isotopic analysis to date the age of trees along the gradient.

**Results:** A significant increase in mangrove cover has occurred in backwaters of the lagoons during the last 40 years, and especially during the El Niño anomalies of the 1980s and 1990s, while at the same time the mangrove fringe has been receding.

**Conclusions:** The observed change can be attributed to the combined action of the warm surface waters of El Niño events and sea-level rise. Jointly, these two effects are sufficient to flood large areas of previously non-flooded salt flats, dispersing mangrove seedlings inland. The inland expansion of mangroves, however, does not ease conservation concerns, as it is the seaward fringes, and not the inland margins, that provide the most valuable environmental services for fisheries and coastal protection.

## Introduction

Recent studies have ranked mangrove forests among the most threatened ecosystems on Earth (Valiela et al. 2001; Alongi 2002; Duke et al. 2007; FAO 2007). In agreement with this view, Mexican governmental agencies have reported that the mangrove area in the nation has been decreasing in the last decades at an annual rate of around −2% (INE 2005). Some large-scale remote-sensing studies in northwest Mexico, however, suggest that mangrove cover in many lagoons, despite common perception, is not being lost. Comparing satellite images, some regional reports have argued that the area covered by mangrove forests has in fact been increasing during the last decades in some lagoons of the Pacific coast of Mexico (de la Fuente & Carrera 2005; Hernández-Cornejo et al. 2005; Hak et al. 2008). Looking at these remote sensing studies in detail, an additional pattern seems apparent: mangrove stands near the open waters, in seaward places such as sand bars or lagoon fringes, have decreased in the last decades, while landward mangrove cover, in the topographically higher edge of the forest, seems to have increased. Furthermore, the different lagoons where this mangrove forest increase has been reported lie in the coastal edge of flat sedimentary coastal plains, where a small change of just a few centimeters in sea-levels could flood large areas of coastal mud flats.


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The rate of forest loss is of environmental concern, as mangroves produce vitally important environmental services, such as coastal protection (Badola & Hussain 2005; Costanza et al. 2008), pollution trapping and regulation of water dynamics in estuaries (Tam & Wong 1997; Ewel et al. 1998; Gilbert & Janssen 1998) and nursery habitat for commercially important fisheries (Costanza et al. 1997; Gilbert & Janssen 1998; Aburto-Oropeza et al. 2008). Cumulatively, the annual value of these services for 1 ha of mangrove forest can add up to tens of thousands of dollars and, in consequence, the long-term discounted value of a hectare of mangrove can reach estimated values of hundreds of thousands of dollars (Costanza et al. 1997; Rönnbäck 1999; Aburto-Oropeza et al. 2008; Hussain & Badola 2008). Thus, when an area of mangrove forest is destroyed, resources that provide valuable services for society may be irreversibly lost. Understanding the balance between mangrove loss and mangrove expansion is of utmost importance for coastal conservation. Thus, the research question driving our study was whether rising sea-levels have induced visible changes in the cover of mangrove forests during recent decades, thus explaining the observed long-term increase in mangrove cover.

Because the existing studies have been done using remote sensing techniques at a regional and relatively large scale, in order to test our hypothesis, we decided to analyse mangrove distribution at a more local scale, where local sea-level, micro-topography and establishment patterns could be measured in detail. For this purpose, we studied the mangrove forests of Magdalena Bay, a 200-km long complex of coastal lagoons in Baja California, Mexico, separated from the Pacific Ocean by a chain of islands and sand bars that keep the bay protected from ocean swells. The inland area east of the bay is formed by a large expanse of desert sedimentary plains that gently slope eastwards for around 50 km, into the foothills of the Sierra de La Giganta.

We explored our hypothesis using five different methods: (a) a comparison of the mangrove spectral signature in satellite images of 1986 and 2001; (b) a time-series analysis of tide levels from long-term recorded data; (c) a comparison of aerial photographs from 1962 against modern high-resolution images; (d) a detailed topographic and floristic field survey along a transect in the coast of the lagoon; and (e) an isotopic analysis of mangrove ages along the fringe–upland gradient.

## Methods

### Comparison of mangrove spectral signature in satellite images

We used seven-band LANDSAT images from 1986 and 2001 for Magdalena Bay, with a pixel size of 28.5 m × 28.5 m, classified into different vegetation categories according to the spectral signature of the dominant ground cover. The images were kindly provided by NatureServe and Pronatura Noroeste, two conservation agencies from the US and Mexico, respectively. The image classification algorithms used the CART (Classification and Regression Tree) software tool (Hansen et al. 1996; Pal & Mather 2003) to model and map the mangrove-dominated community types. Image registration between data sets consisted of 678 co-registration points identifiable on both images. Field surveys were done in March 2007, March 2008 and April 2009 to register community structure and composition of the dominant species, and to verify the results of the classification algorithm. Sites covered by clouds were marked on both images as a polygon shape and removed from the analysis. Adding all pixels that showed a spectral signature attributable to mangrove cover, we estimated the surface area covered by mangrove canopies in 1986 and 2001, and from these values, we estimated the change in mangrove cover in the whole Magdalena Bay from 1 year to another. At a more detailed scale, an image showing mangrove change was developed for Boca de Santo Domingo, one of the flattest plains of the whole region and one of the least impacted by direct human activity.

### Time-series analysis

We downloaded sea-level data from 1950 onwards from the Permanent Service for Mean Sea Level (PSMSL), Proudman Oceanographic Laboratory in Liverpool, UK, (http://www.pol.ac.uk/psmsl/), for three stations in the Californian Pacific: Scripps Pier in La Jolla and San Diego Bay, both in Southern California, and Cabo San Lucas in Baja California Sur, Mexico. All monthly tide levels were re-calculated as deviations from the mean tidal level of 1950, which was taken arbitrarily as zero. Although all the stations had missing values for some months, there were no months in which all three stations had missing values simultaneously.

To obtain an estimate of sea-surface temperature change during the last half-century we downloaded the monthly Multivariate ENSO Index (MEI) from NOAA's Earth System Research Laboratory (http://www.cdc.noaa.gov/people/klaus.wolter/MEI/) from January 1950 (the first available datum) to the present.

Using time-series analysis techniques, we regressed the mean monthly tidal level against individual predictor variables. Because tide levels have an arbitrary origin in each station, we converted all tidal values to deviations from the station's mean. To model the seasonal trends in tide levels (the lowest mean tides are observed around March, when the water is coolest, maximum mean flooding occurs around September, when the water is


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warmest), the first harmonic term in a Fourier analysis was used to model seasonal variations in tidal levels. To capture and quantify the amount of variation that can be attributed to warm water expansion during the warm phase of the Pacific Oscillation (known as ENSO or El Niño Southern Oscillation), we used the MEI values as additional predictors of mean sea-level. In order to detect possible systematic effects of rising sea-levels on the flooding of the coastal mud flats, we used time, measured in years from 1950, as a direct linear predictor. Finally, in order to detect possible differences between stations, we tested for statistical interaction terms between the stations and the three linear predictors (seasonality, MEI and time).

### Hurricane data

In order to test whether extraordinary continental run-off flowing into the lagoon after hurricane storms may have an influence in increased seedling establishment, we obtained the past hurricane tracks in the Pacific coast of North America since 1950 from NOAA's National Hurricane Center (http://www.nhc.noaa.gov), to correlate the occurrence of extraordinary hurricanes with periods of mangrove expansion.

### Evidence from aerial photography

We visited the archives of *Ingenieros Civiles Asociados* (ICA) in Mexico City, the largest collection of aerial orthophotographs in the country, and selected and digitized 53 black and white aerial photographs of the Magdalena Bay region, scale 1:20 000, and taken between 1959 and 1962 (Job 562, Flights 109 and 110). All photographs were scanned at a resolution of 600 dots per inch and saved as JPEG files. Recent (August 2006) high-resolution colour images were downloaded from GoogleEarth Pro. Using ARC MAP software (ESRI, Redlands, CA, USA), images were geo-rectified to correct geometric and spectral distortions using a minimum of ten control points between older images and current INEGI base maps and modern images. The resulting images were projected in the Universal Transverse Mercator co-ordinate system. We used visual interpretation and a simple digital image processor (Adobe Photoshop) to compare geo-rectified past and current images, and to identify changes in mangrove cover. Although we obtained images for the whole estuary, we concentrated our analysis around Boca de Santo Domingo, where a detailed field verification survey was also done.

### Field survey

In April 2009, we established a 425-m transect from a tidal channel to an elevated shell-midden occupied by coastal desert vegetation (25°27′16.5″N, 112°04′20.0″W). With a precision surveyor's level (SOKKIA model C22, Topcon Corp., Japan), we mapped the topographic profile of the lagoon-to-desert gradient, surveying a total of 13 stations. We collected all plants found along the transect, identified them in the lab, and deposited them in the herbarium of the San Diego Natural History Museum as voucher specimens.

On 7 April 2009, at 16:21 h we measured the level of the lowest tide of that day, and on 8 April, at 10:13 h we measured the level of the high tide. Comparing these two values with those from the nearby Port of San Carlos (obtained from CICESE, Laboratorio del Nivel del Mar; http://nivelmar.cicese.mx/), we were able to refer the topographic levels of our transect to those of the coast of the Pacific and thus calculate the mean tidal level for April 2009. Correcting for the effects of season, time and the Pacific oscillation, we then calculated the maximum flooding level in spring 1950, and the maximum flooding levels during the ENSO event of 1997. Finally, we plotted the results in the form of a topographic profile chart.

### Isotope analysis

On 7 April 2009, we collected 2-cm thick stem sections from the base of nine mangrove trees: three were cut from *Avicennia germinans* saplings established in the higher part of the landward hinterland, three from *A. germinans* saplings in the lower part of the hinterland, and three from *Rhizophora mangle* trees in the flooded mud flat forest. In the each of the two hinterland samples, two of the saplings were randomly selected (to get an idea of the modal establishment time), and one additional individual was non-randomly chosen for its larger size with respect to the population (to estimate the establishment time of older saplings). In the mud flat, stem slices were cut from two randomly selected trees, and one was cut from a small tree that looked younger than the rest (to estimate the range of age variation in the mud flat forest). All cross-section slices were oven dried at 60°C until constant weight, and then the stem segments were sliced longitudinally in order to separate the pith from the secondary wood. Because the pith at the base of the stem is the result of primary stem growth, an analysis of $^{14}C$ in the pith cellulose provides an estimate of the plants establishment age.

Holocellulose isolates were prepared from the pith samples and analysed for radiocarbon content. Sample preparation was done at the Facility for Isotope Ratio Mass Spectrometry at UC Riverside and radiocarbon analysis was performed at the Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California, Irvine. Because open-air nuclear explosions in


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the 1950s and early 1960s produced a large increase in atmospheric $^{14}C$, which peaked in 1963-1964 and has been continuously decaying since, radiocarbon samples were classified into pre-bomb pulse and post-bomb pulse. Owing to the availability of aerial photographs of Bahia Magdalena from 1960, where the hinterland mangrove saplings are not visible, we could infer that all bomb pulse-labelled mangroves in the salt flats were established on the falling limb of the atmospheric $^{14}C$-$CO_2$ pulse, i.e. after 1963.

## Results

As reported in other studies from throughout Mexico's northwest, the spectral signature of the mangrove canopy in LANDSAT images increased significantly between 1986 and 2001 (Fig. 1 and Table 1). The net increase concentrates mostly in the landward fringe, where the mangrove forest meets the desert. During the two decades of the study period, a significant area of salt flats became colonized by new mangrove growth.

Mean tidal levels varied ($r^2 = 0.72$) with season and ENSO conditions, and tended to increase linearly with time (Table 2). Each year shows minimum tidal levels around March and maximum levels around September. Additionally, mean tidal levels are also strongly and linearly related to the Multivariate ENSO Index (MEI), a measure of the intensity of the warm El Niño phase in the Pacific Ocean. Finally, mean tidal levels have been increasing since 1950 at a fixed background rate of ca. 2 mm

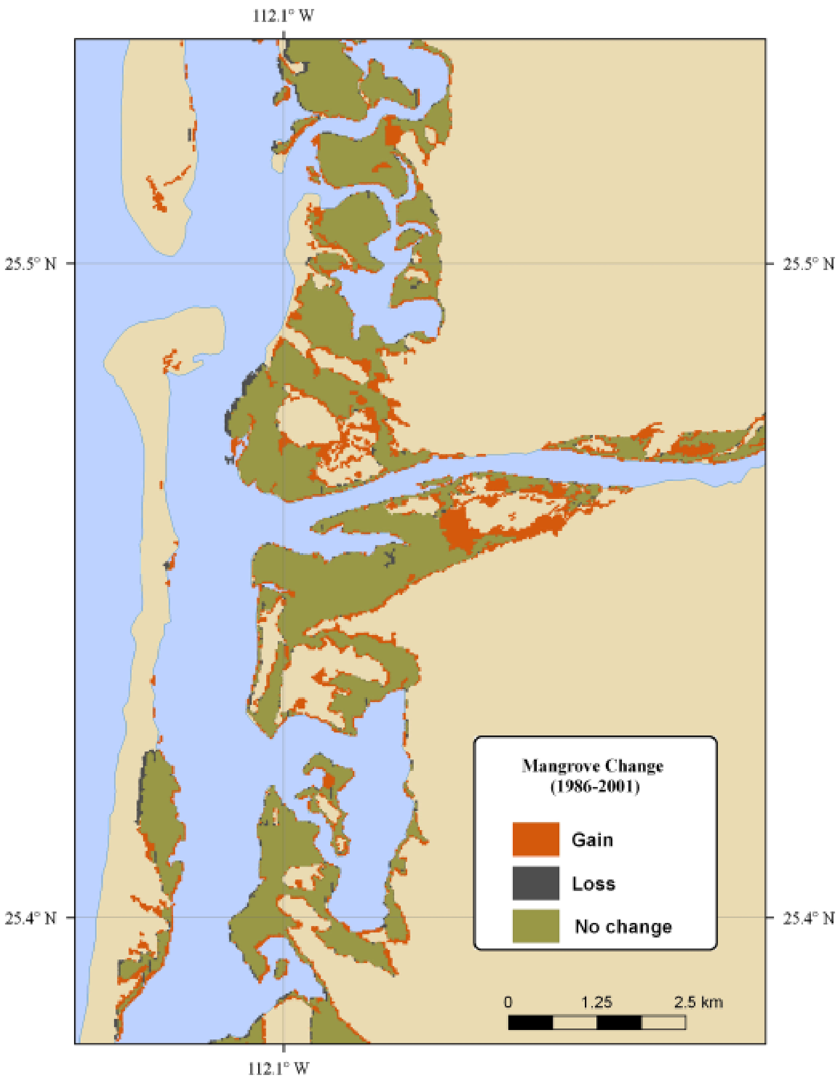


**Fig. 1.** Change in the spectral signature of mangrove canopies between 1986 and 2001, detected in Landsat images near Boca de Santo Domingo, one of the flattest coastal plains in Magdalena Bay and one of the areas least disturbed by direct human action. A trend for mangrove reduction is observed in the lagoon's fringes, while cover tended to increase in the landward edges of the forest.


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per year (Fig. 2). In particular, it was found that during the peak of the El Niño seasons of 1982-1983 and 1997-1998, the tidal levels in the Pacific coast of Baja California were ca. 35 cm above the 1950 baseline level. No significant interaction terms were found between the three tide stations and the predictors, indicating that seasonal variations, El Niño anomalies, and sea -level rise all have a similar effect on each station.

The number of hurricanes and tropical storms reaching the Baja California peninsula since 1950 has oscillated between zero and six per decade (Table 3). There was no visible trend towards increased incidence of tropical storms in recent decades.

Historic black-and-white aerial photos of 1962, compared against modern high-resolution GoogleEarth 2006 images, showed a marked increase in mangrove cover in many flat parts of the lagoon (Fig. 3), basically confirming the results of the satellite image analysis. Because of the fine detail in the aerial images, the error that could potentially be introduced in the satellite images by the large pixel size, or by confusing the spectral signature of mangrove forests with that of halophytes, is much lower in this method. The results showed a marked increase in mangrove cover towards the lagoon's landward fringes.

A topographic transect in the coast of the lagoon showed a narrow association between vegetation types and flooding levels (Fig. 4). The lower mud flat, occupied by high trees of red (*Rhizophora mangle*), white (*Laguncularia racemosa*) and black mangrove (*Avicennia germinans*), was regularly flooded during high tide in 1950. The upper mud flat, occupied by barren, salt-encrusted soils and a sparse community of halophytes, lies above the current level of maximum floods. The band between these two habitats was above the maximum flood level in 1950, but has been undergoing frequent

**Table 1.** Mangrove cover in Magdalena Bay as estimated from the canopy spectral signature in Landsat images 1986–2001.

| Category | area (ha) |
|---|---|
| 1986 – total | 21 081 |
| 2001 – total | 25 730 |
| Unchanged | 19 354 |
| Lost | 1727 |
| Gained | 6376 |

**Table 2.** Significance of different time-series variables driving mean monthly tidal level along Southern California and Baja California. Seasonality was predicted using the first harmonic of a Fourier transform, the intensity of the El Niño phenomenon was derived from the Multivariate ENSO Index (MEI), and the effect of continuous sea level rise was estimated using time as a linear predictor. No significant differences were found between the three tide stations.

| | SS | df | MS | *F* | *P* | $r^2$ |
|---|---|---|---|---|---|---|
| Seasonality | 4 614 347 | 2 | 2 307 174 | 1221 | < 0.00001 | 0.43 |
| El Niño anomalies | 2 267 594 | 1 | 2 267 594 | 1200 | < 0.00001 | 0.21 |
| Global sea level rise | 819 650 | 1 | 819 650 | 434 | < 0.00001 | 0.08 |
| Full model | 7 701 591 | 4 | 1 925 398 | 1019 | < 0.00001 | 0.72 |
| Error | 2 982 112 | 1578 | 1890 | | | |

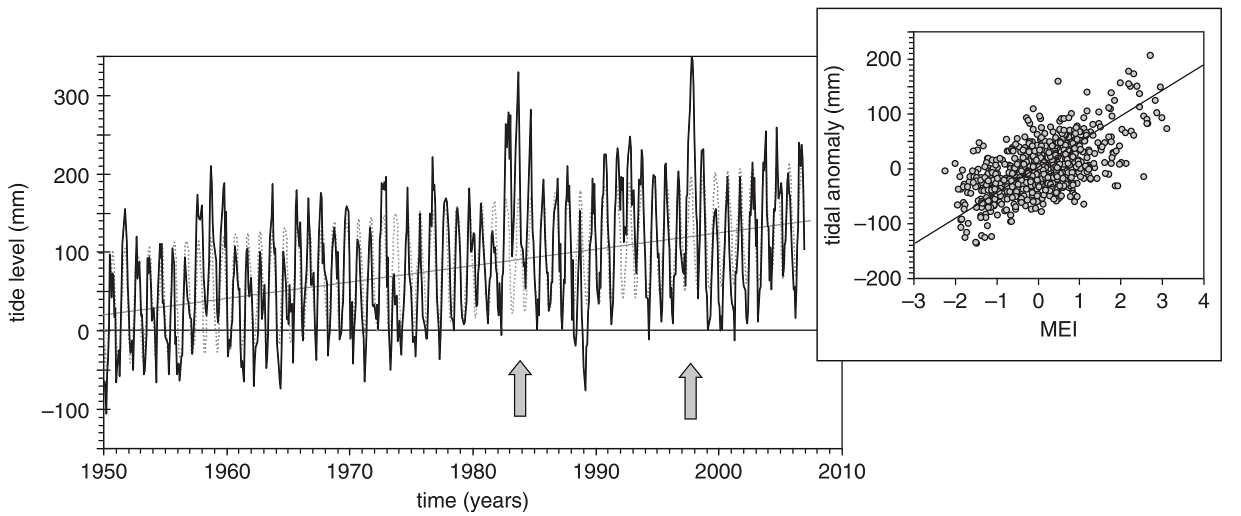


**Fig. 2.** Monthly mean sea-level values for the Pacific coast of Baja California. The data line in black shows the averaged values of the three tide stations (Scripps, San Diego and Los Cabos), arbitrarily taking the mean tidal level for 1950 as the baseline origin. The straight line in grey indicates the general trend for sea-level rise, the sinusoidal broken line shows the harmonic function describing seasonal variation. The deviations from these two predictors, shown in the insert to 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 salt flats.


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**Table 3.** Number of hurricanes and tropical storms hitting the Baja California peninsula and generating increased continental runoff into the Magdalena plains.

| Decade | Storms |
|---|---|
| 1950–1959 | 5 |
| 1960–1969 | 3 |
| 1970–1979 | 2 |
| 1980–1989 | 0 |
| 1990–1999 | 2 |
| 2000–2009 | 6 |

inundations since, as sea-level has gradually risen. This band is now colonized mostly with young saplings of black mangrove, whose canopies show up in the satellite images as new mangrove cover.

The results of the isotopic analyses (Table 4) were strongly consistent with those of the photographic analysis and the field survey. The randomly selected plants sampled in the upper hinterland, the highest part of the transect, showed contemporary establishment times (the pith was formed after the 1998 ENSO event), while saplings in the lower hinterland showed piths formed after 1987 (following the 1983 ENSO event). In contrast, the randomly selected trees in the mud flat forest were 80 to 135 years old, with a younger, selectively chosen individual reaching ca. 37 years of age.

## Discussion

During the last two decades, the area covered by mangrove canopies has increased in Magdalena Bay by more than 20%. Mangrove saplings are now growing in the landward stretches of the mud flats, which were occupied decades ago by salty soils and a halophytic desert scrub. It is clear from our transect data that microtopography is a major factor in the response of vegetation to changes in sea-level. Inland colonization by mangrove saplings will chiefly happen in gently sloping coastal plains, where a slight increase in sea-level may significantly drive the intrusion of seawater inland.

The process of inland colonization necessarily demands extraordinary tidal levels flooding the coastal salt flats, as flooding depth is one of the main factors defining the establishment of the viviparous propagules of mangroves (Rabinowitz 1978). The larger propagules of the red mangrove tend to become established in the deeper parts of the intertidal mud flats, while the smaller propagules of the black mangrove can drift inland into shallow waters. Thus, maximum tidal level defines the vegetation composition of any given point within a mud flat. In congruence with this, the newly colonized salt flats in Magdalena Bay contained saplings of black mangrove, the species with the smallest propagules.

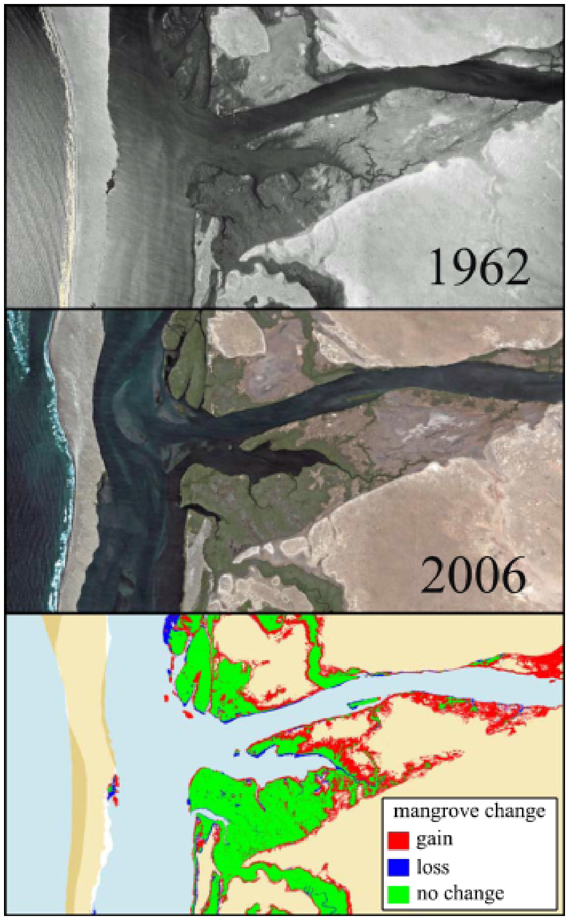


**Fig. 3.** Boca de Santo Domingo in high-resolution images. The top plate shows an aerial photograph taken in 1962, the middle one is a GoogleEarth image from August 2006. The image at the bottom highlights the differences between the two timed photos.

The new colonization of the previously mangrove-bare salt flats may be triggered by at least three different phenomena: (a) extraordinary continental run-off flowing into the lagoon after hurricane storms; (b) very strong ENSO warm-phase anomalies; or (c) continuously rising sea-levels. Hurricanes, however, have occurred regularly in the past (Table 3), and there is no strong evidence of increased continental run-off during the last three to four decades, the period in which new mangroves have colonized the mud flats. Furthermore, there is good evidence that hurricane-driven floods were in the past as strong as they are today: in 1906 the American explorer Edward W. Nelson documented an extraordinary flood that inundated the whole of the Magdalena plains and the surrounding desert vegetation: "*for two days we had the strange experience of riding through desert vegetation immersed in water as though growing in a marsh*" (unpublished notebook, Smithsonian archives). Remarkably, during the decade 1980-1989, a period where according to isotopic


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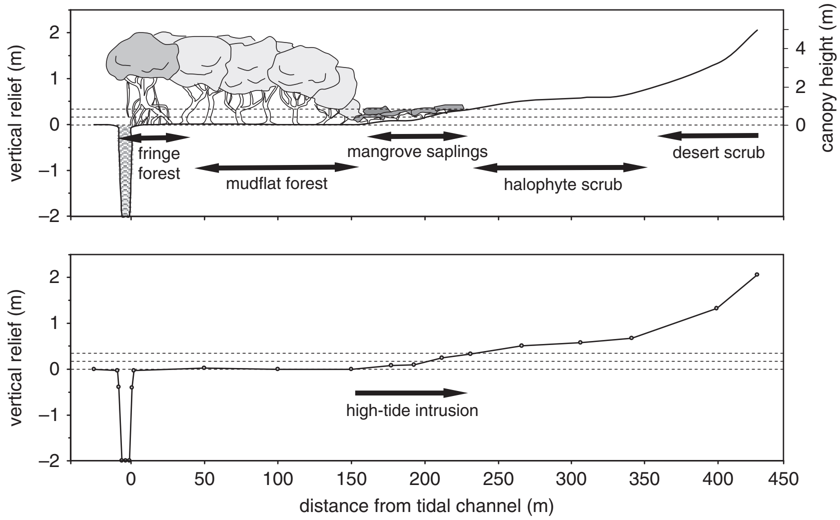


**Fig. 4.** Top: Vegetation profile of the mangrove community in Boca de Santo Domingo, Magdalena Bay. The fringe forest is formed by linear stands of the stilt-rooted red mangrove (*Rhizophora mangle*); the mud flat forest is composed of old-growth stands of red, black and white mangroves (*Rhizophora mangle*, *Avicennia germinans* and *Laguncularia racemosa*, respectively), and the saplings in the landward edge are mostly small individuals of black mangrove. Bottom: The same profile with the topographic stations. The lower dotted line shows the high-tide flooding levels in 1950, the middle dotted line shows the high-tide levels observed in April 2009, and the upper dotted line shows the levels of high-tide inundation during the El Niño season of 1997. The distribution of mangrove saplings, which were not seen in the 1962 aerial photograph, is concentrated in the upper landward edge that was flooded in recent decades.

**Table 4.** Carbon age of nine trees along the sampling transect, classified by their landform position along the topographic gradient, and the sampling criterion used to select them.

| species | Landform | sampling criterion | year |
|---|---|---|---|
| *Avicennia germinans* | upper hinterland | older plant | 1986 |
| *Avicennia germinans* | upper hinterland | Random | 2007 |
| *Avicennia germinans* | upper hinterland | Random | 2007 |
| *Avicennia germinans* | lower hinterland | older plant | 1973 |
| *Avicennia germinans* | lower hinterland | Random | 1990 |
| *Avicennia germinans* | lower hinterland | Random | 1988 |
| *Rhizophora mangle* | Mudflat | Random | $1929 \pm 20$ |
| *Rhizophora mangle* | Mudflat | Random | $1874 \pm 20$ |
| *Rhizophora mangle* | Mudflat | Sapling | 1972 |

observations mangrove seedling establishment in the mud flat was intense, there were no recorded hurricanes or tropical storms in the region.

Seedling establishment in the newly colonized areas has occurred mostly since the 1970s, in coincidence with a period of frequent and strong El Niño events. Thus, it is likely that these oceanic warm-phase anomalies had a strong influence on the inland colonization by mangrove seedlings. It is likely, however, that all three causes may be working in a synergistic fashion. Williams (2009) described how extraordinary oceanic anomalies and unusually strong hurricanes can set the stage for sea-level rise to drive rapid changes in coastal landforms delivering a "combination punch" to the coastal systems.

Following this idea, and based on our establishment data, it is likely that mangrove inland expansion progressed in pulses, driven by the warm phase of the ENSO anomaly, which can episodically add 20 cm or more to the background trend for sea-level rise. During the ENSO seasons of 1982-1983 and 1997-1998, the lower salt flats of Magdalena Bay became regularly flooded with the high tides, and mangrove establishment followed. Continuous sea-level rise, on the other hand, has kept these mud flats wetter than they were only a few decades ago, allowing the newly established seedlings to survive. At the same time, a significant amount of mangrove fringe has been lost (Fig. 5).

The inland expansion of mangroves as a result of rising sea-levels, however, does not ease concerns for the future of these ecosystems. An area occupied by new-growth mangrove saplings may have a canopy spectral signature similar to that of a mature forest, but ecologically it does not have the complexity of an old-growth stand. At the same time, many areas of fringe mangrove have been suffering considerable loss (Whitmore et al. 2005) as a result of forest clearing, dredging, sedimentation, increased wave action from motorboats and, as this paper now shows, also as a result of increased sea-levels. Recent papers have demonstrated that these seaward fringes provide the most valuable environmental services, such as fisheries or coastal protection (Barbier et al. 2008; Koch et al. 2009). A recent study by our research group (Aburto-Oropeza et al. 2008) showed that the annual

**Fig. 5.** Top: Receding seaward fringe of the mangrove forest (exposed black mangrove root system near Puerto López-Mateos). Bottom: High desert hinterland becoming colonized by black mangrove saplings (salt-flat near Boca de Santo Domingo).

value of the fisheries services provided by fringe mangroves can be of the order of US$37 000 per ha. Because a large part of the 1727 ha of mangroves that have been lost in Magdalena Bay during the last decades corresponds to fringe mangrove, it is likely that many millions of dollars in fishery habitat have been lost or degraded as a result of rapid changes in the mangrove forests.

The on-going colonization by small black mangrove saplings in the landward part of the tidal flats does not necessarily compensate for the loss of old-growth mangrove forest in the seaward fringe. Mangroves have been clearly responding to sea-level rise, but the benefits of increased mangrove establishment in the landward salt flats, compared to the loss of valuable services as a result of mangrove destruction in the seaward fringe, are dubious.

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