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Restoration and recovery of hurricane-damaged mangroves using the knickpoint retreat effect and tides as dredging tools

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A R T I C L E I N F O

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This study is dedicated for the memory of the Mexican mangrove researcher Dr. Gina Holguin (1957–2007) of CIBNOR, Mexico who made the initial survey of this ecosystem.

Keywords:
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Mangrove
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A B S T R A C T

In 2001, a hurricane moved a large sand dune, blocking the sole outlet channel of a mangrove. In the absence of daily tidal flow, the two ponds containing the mangrove vegetation evaporated, the secondary drainage channels were lost, and a salt crust formed on the bed of the ponds. The mangrove lost most of its trees and the remaining suffered from osmotic shock that led to defoliation. Restoration involved creating a knickpoint retreat (waterfall retreat effect) and tidal flow as a dredging mechanism to restore the outlet and form secondary channels in the ponds. During a very low tide, we deepened the mouth of the outlet channel by 1 m below high tide level to form a small waterfall when high tides receded. During successive tides, this one-step knickpoint deteriorated and formed a series of low rapids. With a steep gradient, the rapids retreated upstream into the ponds, first reopening the outlet channel and then carving new secondary channels in the pond mud flat. The excavation process of the outlet channel was repeated three times and was sufficient to effectively improve the hydrology of the entire pond system; allowing adequate flooding and draining of the mangrove ponds. Hydrology analysis tested by the Engelund–Hansen sediment transport formula established that the output of sediment from the ecosystem is greater than the input of sand into the mangroves. This is keeping the main channel continuously open. After eight years, tidal flow continues to keep the channels open; the salt crust has disappeared; the trees have recovered, and a large area of new vegetation has emerged.

1. Introduction

Mangrove forests are vital tropical marine coastal ecosystems located at the intertidal zones of estuaries, backwaters, deltas, creeks, lagoons, marshes, and mud flats in tropical and subtropical regions (Spalding et al., 2010). Mangroves are continually destroyed by coastal development and aquaculture facilities. Since the 1980s, over 35% of mangroves worldwide have been lost (Valiela et al., 2001) and more than 50% have been destroyed in recorded history (FAO, 2007; Polidoro et al., 2010). Duke et al. (2007) predict that a world without mangroves is a realistic scenario if the destruction of mangrove ecosystems continues.

Mangroves provide essential environmental services, acting as safe havens and breeding grounds for countless marine species and waterfowl and an irreplaceable prerequisite for coastal fisheries in the tropics (Holguin et al., 2001) and carbon sink to mitigate climate change (Alexander et al., 2011; Donato et al., 2012). Mangroves act as critical barriers that protect coastal cities and rice fields from tropical storms and tsunamis, mainly in Asia (Barbier, 2006; Dahdouh-Guebas et al., 2005; Das and Vincent, 2009). Although mangroves in the wet tropics are easy to reforest, even by the simplest means (Walton et al., 2006), mangroves in arid and semi-arid environments are especially sensitive and have difficulty regenerating after disruption (Toledo et al., 2001; Vovides et al., 2011a).

Restoration and rehabilitation of mangroves require a variety of methods and procedures, depending on the characteristics of the site, its location, and the funds available (for reviews: Bosire et al., 2008; Ellison, 2000; Field, 1998; Kaly and Jones, 1998). There are three major approaches: (1) The most common is planting of saplings, seedlings, and propagules (Bashan and Holguin, 2002; Bosire et al., 2003; Chen et al., 2004; Das et al., 1997; Gilman and

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Ellison, 2007; Hashim et al., 2010; Kitaya et al., 2002; Macintosh et al., 2002; Moore, 2004; Naohiro et al., 2012; Ren et al., 2008; Saenger and Siddiqi, 1993; Toledo et al., 2001; Walters, 2000; Zan et al., 2001); (2) Natural recruitment of propagules (Bosire et al., 2003; Kairo et al., 2001; Kamali and Hashim, 2011; Vovides et al., 2011a); and (3) The least common, restore hydrologic conditions that remove stress, followed by planting or natural re-vegetation (LaSalle et al., 1991; Lewis, 2005; Milano, 1999; Turner and Lewis, 1996; Vose and Bell, 1994).

This mangrove was damaged by a hurricane that blocked the sole outlet with a sand dune, eliminating the daily flushing action of tides. Consequently, the forest was severely degraded by the disruption of normal hydrologic action. Our working hypotheses were that: (1) Restoring normal hydrology will rehabilitate this mangrove; (2) A combination of forming a knickpoint retreat (waterfall) with normal tidal flow for a prolonged period will clear and maintain the outlet channel and create secondary channels; this will re-vitalized the degraded mangrove trees. The objectives of this study were: (1) To create a low waterfall by deepening the mouth of the outlet channel. This will induce hydrologic change that will remove sediments from the mangrove ponds. (2) Hydrologic analysis to establish the reasons behind the continuous functioning of the mangrove ecosystem and, (3) Monitor the effect of hydrologic restoration on the well being on the trees over several years.

2. Material and methods

2.1. Study area and its history

The restored area, which lies opposite the city of La Paz in the State of Baja California Sur, Mexico, is part of a series of arid zone sites consisting of numerous small mangroves that cover the shore of the long sandbar, called El Mogote, that separates the large bay, Bahía de La Paz, from the 50 km^2 lagoon (24°08′N, 110°23′W), called Ensenada de La Paz (for survey: Holguin et al., 2006). Currently, the restored area has high urban pressure because of a large-scale, urban development bordering the mangrove patches, including a golf course, high-rise condominium towers, and a large single-family residential area. The ponds contain three mangroves species: *Rhizophora mangle* L. (red mangrove), *Laguncularia racemosa* Gaertn. (white mangrove), and *Avicennia germinans* (L.) Stern (black mangrove), which are common in mangroves in this region (Toledo et al., 2001; Vovides et al., 2011a). The mangroves of El Mogote serve as nesting grounds for several threatened marine shorebirds, including one species in danger of extinction (Holguin et al., 2006). Tidal amplitude is ~1.5 m, with monthly variations of 1.30–1.72 m http://redmar.cicese.mx/CGM/cgm07.html, accessed 6 July 2011).

In late summer 2001, a hurricane passed through Bahía de La Paz, moving a large sand dune across the outlet of one of the mangroves (Figs. 1a, 2a); the mangrove consists of two shallow ponds (~10 ha). We define a pond as a shallow extension of the lagoon that collects seawater from daily tidal flow through the channel that connects the ponds to the lagoon. At that time, this area was inaccessible by car, relatively remote, and used only by local fishermen and bird watchers. The environmental authorities were not alerted. Because there is no documented information how the blocking occurred, we assumed that, in the absence of daily tidal flow, the mangrove slowly deteriorated. Many trees died and the rest suffered from osmotic shock that led to complete defoliation. With time, the two ponds lost all of their secondary mud channels, probably filled by dust and fine sand transported by moderate winds. After evaporation of the seawater, a salt crust covered the pond bed (Fig. 1b). In early 2003, a land developer requested a construction permit to convert a large portion of the tip of El Mogote sand spit into a major residential development and replace the damaged mangrove with a small shopping center. An official survey of the area, required by the permitting process, outlined the damaged mangrove (Holguin et al., 2006). In autumn 2003, a passing hurricane partly removed the sand dune blocking the channel, but this was not sufficient to open an outlet for the mangrove. A formal request for restoration was submitted to the Mexican environmental authority (SEMARNAT). The approved permit prohibited construction of any permanent installation to regulate the water flow, but allowed use of local stones without cement or iron reinforcement.

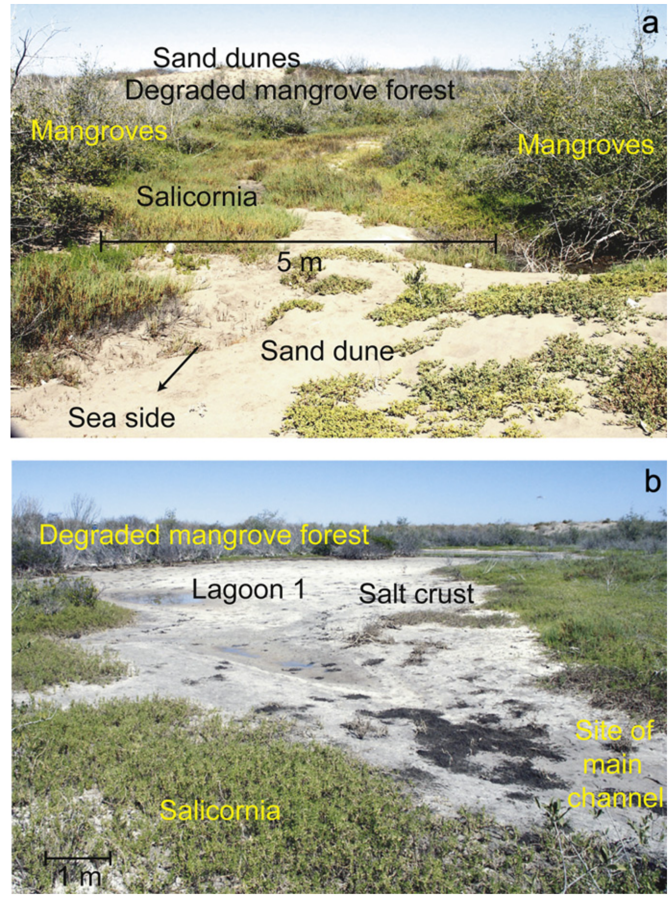

Fig. 1. (a) The blocked main channel of the mangrove ponds on the sand barrier bar called El Mogote. The original channel is clogged with sand and covered with the dwarf saltwort *Salicornia bigelovii*. (b). Pond #1 before restoration. The salt crust and most trees are severely affected or dead.

2.2. Measurements of the mangrove area and recording vegetation before and after restoration

Measurements were obtained from satellite images from the Instituto Nacional de Estadistica y Geografia (INEGI), Mexico and Google Earth and verified in the field by GPS. Photographs of the mangrove area were taken. The area was measured by creating 9 transects (2004) and dividing the entire area into 7 m × 10 m rectangles (2009). A vegetation inventory was made for each rectangle, either directly from the image (for general vegetative cover) and for the tree species by: (1) Field observations of the locations in February 2009 and (2) Field photography of the entire site in 2004; only live trees were recorded. Data was analyzed by Student's t-test at $P < 0.05$. Values in percentage were arcsin-transformed before analysis.