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Application of a simple and effective method for mangrove afforestation in semiarid regions combining nonlinear models and constructed platforms

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ABSTRACT

The strength and frequency of local tides in coastal lagoons plays a crucial role in providing suitable locations for the establishment of mangrove seedlings. Hence, the purpose of this investigation was to assess the hydrodynamics of a meandering tidal channel in order to select optimal locations for the construction of platforms, and thus improve the recruitment of white mangrove (*Laguncularia racemosa*) and red mangrove (*Rhizophora mangle*) propagules. The study was conducted within a coastal lagoon located along the semiarid coast of the Gulf of California. Current velocities and vorticity were simulated during flood and ebb tides using nonlinear numerical models. We tested three platforms of $3 \times 3 \times 0.5$ m and measured the velocity and vorticity again. Once the model predicted locations where the ratio between friction and advective terms were greater, we proceeded with the construction of platforms in such suitable locations. The platforms presented a wooden perimeter filled with sediment at a similar height of the nearby mangroves (i.e., + 0.5 m Mean Sea Level). One platform was afforested with 50 red mangrove propagules, while the remaining two platforms were left without plants. Results indicated that the platforms without plants were quickly invaded by white mangrove propagules. Contrary to the aforementioned, the platform with red mangrove propagules was not invaded or replaced by other mangrove species. After nine years, the two platforms with white mangroves present 60 and 40 trees with a height of 3.5 ± 0.5 m, while the red mangrove platform presents 25 trees with a height of 3 ± 0.5 m. Our study showed the feasibility of combining numerical models and constructed platforms in order to create mangrove islands in semiarid coastlines.

1. Introduction

Mangrove forests are valuable ecosystems distributed in the intertidal zone along tropical and subtropical coastlines (Tomlinson, 1994). It is well known that maintaining healthy mangrove ecosystems provides adaptive capacity to protect coastal zones (Gedan et al., 2011) against wave action (Horstman et al., 2014; Thornton and Johnstone, 2015), erosion (Anthony and Gratiot, 2012; Horstman et al., 2015), and flooding (Lewis III and Brown, 2014), due to tropical storms (Das and Crépin, 2013), hurricanes (Sandilyan and Kathiresan, 2015), and even tsunami events (Dahdouh-Guebas et al., 2005; Danielsen et al., 2005). They are of utmost importance for local communities (Walters et al., 2008; Abdullah et al., 2016), present high productivity (Komiyama et al., 2008), enhance climate change mitigation acting as carbon sinks (Bouillon, 2011), and as nursery stations for many important species of terrestrial and aquatic fauna (Buelow and Sheaves, 2015), especially in arid (AboEl-Nil, 2001; Al-Maslamani et al., 2013) and semiarid systems (Flores-Verdugo et al., 2015). Despite their ecological relevance and numerous ecosystem services (Tuan Vo et al.,

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2012; Carter et al., 2015), mangrove forests have suffered a global loss of 35% during the last two decades (Valiela et al., 2001) associated with aquaculture expansion (Duke et al., 2007; Polidoro et al., 2010), coastal development (Mukherjee et al., 2014), and climate change effects (Alongi, 2015) such as sea-level rise (Webb et al., 2013; Lovelock et al., 2015). Consequently, increasing recognition from the society about the negative ecological effects of mangrove loss (Datta et al., 2012), as well as the worldwide estimated cost of ecosystem services provided by mangroves at US $1.6 billion per year (Polidoro et al., 2010), have created a need to better understand the biophysical drivers of mangrove forests (Schmitt and Duke, 2015), including the establishment of seedlings on unvegetated tidal flats (Balke et al., 2015).

In response to the loss of coastal areas, the need to preserve and restore mangroves has been widely recognized in the scientific community. In this sense, Lewis III and Brown (2014) described the biophysical factors that influence mangrove establishment and early growth in detail. In another study, Schmitt and Duke (2015) discussed mangrove conservation and planting efforts by assessing the advantages and disadvantages of common techniques such as replanting, rehabilitation, restoration, and afforestation (i.e., habitat conversion). From these works, it is clear that the number of mangrove projects has increased worldwide but most of them have utterly failed or have failed to achieve their original objectives because active planting has been the most common method employed. For example, the survival rate of plantation in the Philippines was 10–20% (Primavera and Esteban, 2008); 50% in Bangladesh (Saenger and Siddiqi, 1993); less than 50% in Vietnam (Que et al., 2012), and a Guinness World Record set in 2013 in Pakistan where 847,275 saplings were planted in one day but, unfortunately, it has been estimated that the actual survival rate could be less than 30% as they were not planted during an optimal season (http://news.trust.org//item/20131203123452-q63ki/).

There are many factors contributing to the large scale failure of mangrove planting projects. Lewis III (2005) found that lack of hydrological knowledge was the most common cause leading to major loss of planted seedlings. In this sense, tidal elevation and flooding areas determine when an established mangrove seedling will experience disturbance (Balke et al., 2014). This is followed by the magnitude of external forces such as wave height, which determines how strong the disturbance could affect the seedlings. Additionally, early planted seedlings could be impacted by minimal protection from strong winds (Kamali and Hashim, 2011) and sedimentation (Tamin et al., 2011). Hence, it is necessary to understand the ecological principles of planting mangroves before starting any mangrove project. Moreover, recent studies suggest that a combination of hydrological modeling, ecology, and engineering works should be considered to coastal adaptations for successful mangrove plantation, rehabilitation, restoration or afforestation endeavors (e.g., Cheong et al., 2013; Milbrandt et al., 2015).

Considerable effort has been devoted to studying the hydrodynamic processes in mangrove forests (see reviews by Lewis III, 2009; Seenath et al., 2016). The first numerical, depth-averaged models of mangroves were used to study flow through tidal channels. These models simulated vegetation-induced friction through an adjusted roughness factor with constant elevation (e.g., Wolanski et al., 1980; Wattayakorn et al., 1990). Mazda et al. (1995) derived analytical models for tidal flow in a theoretical linear channel with fringed mangrove vegetation using a 2-D depth-integrated model. In their model, the response of mangrove trees was incorporated as an overall increase in the drag coefficient. Furukawa et al. (1997) studied tidal currents, cohesive sediment, and organic carbon transport in a highly vegetated mangrove forest of Australia. Results showed that about 80% of the suspended sediment was trapped in the sheltered mangrove trees. Kamali et al. (2010) used a combination of mangrove restoration schemes with low crested breakwaters in an intertidal zone in Selangor, Malaysia. Results indicated that the presence of breakwaters resulted in sediment deposition allowing mangrove establishment on a more suitable soil height. Tamin et al. (2011) achieved seedling establishment of *Avicennia marina* (Forsk.) Vierh following the construction of segmented breakwaters in order to reduce coastal erosion. Wu et al. (2001) developed a two-dimensional, depth-integrated model in order to assess the effects of vegetation-induced drag force and the friction generated by mangroves. Results revealed that the flow velocities were reduced by mangroves in the forested area, while the main channel presented an increase in the current velocities. Bashan et al. (2013) restored a hurricane-damaged mangrove area in an arid coastline of Mexico by creating a knickpoint retreat effect. After eight years, tidal flow continues to maintain the channel open and soil hypersalinity was decreased enhancing the establishment of mangrove seedlings. Balke et al. (2015) applied a mechanical model according to the window of opportunity concept, which analyzes real time series of external forcing. Results indicated that temporary reduction of external forcing would lead to a sudden progradation of the mangrove forests. Flores-Verdugo et al. (2015) constructed a series of experimental channels in order to reduce pore-water hypersalinity in an upper saltpan area and enhance black mangrove (*Avicennia germinans* (L.) Stearn) survival and growth. Results indicated that salinity concentration was decreased by half of the initial concentration after ten months. Horstman et al. (2015) developed a model that considers depth dependency of vegetation. Results showed that the creeks are found to form the major pathway for the tidal inflow during the lower tides, while the protected interior of the mangroves acted as an effective sediment sink during the higher tides.

Many studies have shown that mangrove forests are limited to specific substrate elevations relative to tidal level, inundation time, or inundation frequency (e.g., Van Loon et al., 2007; Bosire et al., 2008; Zaldívar-Jiménez et al., 2010; Yang et al., 2013; Costa et al., 2015). Additionally, once the site-selection for mangrove planting has been selected, numerous site characteristics should be considered, for example, the stability and composition of the soil, degree of exposure to waves and strong currents, availability of freshwater, presence of pests, and availability of propagules (Field, 1998). However, most of the hydrological regime (i.e., duration, depth, and frequency of inundation) shows very different thresholds among the mangrove species and locations. Thus, the key is to find the correct hydrological conditions for the specific mangrove species to survive (Lewis III, 2005).

In general, studies from flume experiments (Balke et al., 2011), simulated tidal systems (Monroy-Torres et al., 2014), and dynamic coasts such as New Zealand (Lovelock et al., 2010), Thailand, British Guyana, and Suriname (Winterwerp et al., 2013) show that currents, waves, and sediment transport induced by tidal flooding play a key role in controlling mangrove seedlings establishment. For instance, only a few studies have observed the effects of hydrodynamic forcing by currents and waves on seedling establishment success (Flores-Verdugo et al., 2007; Benitez-Pardo et al., 2015; Balke et al., 2015). In this regard, the construction of mudflats, channels, and ponds as part of mangrove projects would alter sediment deposition processes in mangrove swamps (Shih et al., 2015). Thus, in this study, we evaluated the hypothesis that increasing soil height at specific locations where minimum residual current is presented will enhance mangrove seedlings recruitment and growth. The objectives of this study were: (1) to select an optimal site for mangrove afforestation in a meandering tidal channel by using nonlinear numerical models; (2) to construct sediment platforms at the optimal height of white mangrove (*Laguncularia racemosa* (L.) Gaertner *f.*) and red mangrove (*Rhizophora mangle* L.) in the selected sites; and (3) to quantify the growth of both species.