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The role of surface elevation in the rehabilitation of abandoned aquaculture ponds to mangrove forests, Sulawesi, Indonesia

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ABSTRACT

Intertidal mangrove forests are declining rapidly in Southeast Asia due to diverse threats such as urbanisation, agriculture and aquaculture. Mangrove rehabilitation programmes designed to compensate for such declines are largely unsuccessful as they fail to match environmental conditions to species-specific tolerance thresholds for different mangrove vegetation species. This study investigated the importance of surface elevation (related to tidal inundation period) in influencing the colonisation and establishment of mangroves in a rehabilitation site in Sulawesi, Indonesia. A topographic survey of 29 abandoned aquaculture ponds was conducted to map the surface elevations before and shortly after rehabilitation. A vegetation survey was conducted in a neighbouring reference forest to quantify the surface elevation envelopes of established mangroves, and in the rehabilitated site to predict where successful vegetation establishment would occur, and to guide remedial works to make surface elevations suitable for establishment. Surface elevations in aquaculture ponds ranged between −2.158 m and 2.411 m WGS 84. 651 mangrove individuals across 13 species had established naturally in ponds within six months after rehabilitation, and were restricted to elevations of −1.511 m to 0.228 m WGS 84. Seedlings/saplings from both ponds and reference forests had established at comparable surface elevation ranges of −1.511 m to 0.228 m WGS 84 and −1.255 m to 0.073 m WGS 84. The elevation envelope occupied by seedlings in aquaculture ponds was widest for *Avicennia rumphiana* (−1.085 m to −0.218 m WGS 84) and in reference forests, *Rhizophora mucronata* (−0.850 m to −0.503 m WGS 84). This study highlights the importance of intertidal surface elevation and its control on inundation hydroperiod as a key, spatially explicit threshold to seedling colonisation establishment. The rehabilitation of appropriate surface elevations is a crucial first step in successful mangrove rehabilitation.

1. Introduction

Human exploitation and conversion of natural ecosystems is causing widespread ecosystem loss and degradation, with concomitant declines in biodiversity and ecosystem service provision (e.g., Butchart et al., 2010), especially in the tropics. The potential of ecosystems to recover from such losses can be driven by natural secondary succession, or can be engineered through ecological rehabilitation, where secondary succession is aided by humans (Lugo, 1999; Simenstad et al., 2006; Elliott et al., 2007; Stein and Cadien, 2009), to produce self-sustaining and resilient ecosystems (Borja et al., 2010). Estuarine, coastal and marine ecosystems in particular require extensive rehabilitation, as these habitats are experiencing increasing rates and extent of loss and degradation, caused by single, cumulative or synergistic processes stemming from primarily anthropogenic sources (Lotze et al., 2006; Doney et al., 2012).

Intertidal mangrove forests are declining at a rapid rate (Duke et al., 2007), which in Southeast Asia is primarily due to agriculture and aquaculture (Hamilton, 2013; Richards and Friess, 2016). In particular, mangroves are converted into aquaculture ponds, and a large proportion of such ponds are abandoned after 5–10 years as intensive aquaculture is rarely sustainable over the long-term (Flaherty and Karnjanakesorn, 1995). Abandoned ponds are potentially suitable for mangrove rehabilitation, once socio-political issues relating to land tenure and community participation are

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overcome (Hoang Tri et al., 1998; Primavera, 2000; Walters, 2003; Nguyen et al., 2016).

The number of mangrove rehabilitation programmes worldwide is extensive, conducted mostly to restore forest cover and habitat functionality (Katon et al., 2000; Barbier, 2006). "Rehabilitation" in this case, is defined as the act of partially or fully replacing the structural or functional characteristics of an ecosystem that have been diminished or lost and is distinguished from "restoration", which aims to return an ecosystem back to its original condition (Field, 1999). Many rehabilitation programmes in Southeast Asia are conducted through the planting of mangrove propagules and/or seedlings, which commonly results in low survival rates. For example, two World Bank-funded mangrove rehabilitation projects in the Philippines had estimated survival rates of only 17–35.2% over 11 years, at a cost of $73 million (Central Visayas Regional Project and Community-Based Resource Management Program; Primavera and Esteban, 2008). Reasons for low survival rates at the site-scale include – (i) inappropriate site-selection; (ii) choice of inappropriate species (i.e. failure to consider biological inundation thresholds of replanted species); and (iii) failure to account for site-specific physical conditions such as hydrology (Primavera and Esteban, 2008; Samson and Rollon, 2008; Friess et al., 2012; Brown et al., 2014b). Afforestation (i.e. establishing trees on land which historically have not contained forests; IPCC, 2000) projects often support planting on low-elevation mudflats (where mangroves did not previously exist) because restorers are unable to resolve landward land tenure issues, or require a large open space for planting (Lewis and Brown, 2014). This often results in the monospecfic planting of commercially attractive, but non-pioneer species (e.g. *Rhizophora* spp.) that are not suited for establishment on low elevation, sub- or inter-tidal zones such as sandflats, mudflats and/or seagrass beds.

Rehabilitation programmes are most successful if they match environmental conditions (such as tidal inundation, salinity, soil nutrient status) to species-specific thresholds of tolerance for different mangrove species (Friess et al., 2012). While many rehabilitation efforts in Southeast Asia are still based on monospecific plantings on often unsuitable low-elevation locations, some efforts are now shifting towards creating suitable environmental conditions that promote natural regeneration. The Ecological Mangrove Rehabilitation (EMR) approach (Lewis and Marshall, 1997; Lewis, 2005; Brown et al., 2014a; Lewis and Brown, 2014) practices this philosophy over several steps. Firstly, biophysical reasons accounting for mangrove loss and limiting natural regeneration (via secondary succession) should be assessed before rehabilitation commences. Thereafter, rehabilitation should work *within* the physical boundary conditions that control mangrove establishment and survival, such as tidal hydrology, flushing, wave action and suspended sediment supply (Lewis, 2005; Lewis and Gilmore, 2007; Chen et al., 2012; Winterwerp et al., 2013; Balke and Friess, 2016). Though the physical, chemical and ecological factors affecting mangrove establishment are numerous and complex (Krauss et al., 2008), inundation, linked to the surface elevation of the rehabilitation site, is one of the primary factors because of its direct influence on the establishment, survival and growth of mangroves (Lewis, 2005; Gilman and Ellison, 2007), and its influence on secondary factors such as oxygen availability, salinity and pH (Krauss et al., 2008).

The influence of inundation and surface elevation in determining establishment success (Lewis, 2005; van Loon et al., 2016) is such that elevation manipulation may be conducted within a site to establish elevation ranges comparable to a neighbouring reference wetland (*sensu* Stanley and Lewis, 2009). Such activities are conducted in temperate and sub-tropical wetland rehabilitation (e.g. Stagg and Mendelssohn, 2011; Lewis, 1990), though only a few examples exist for tropical mangrove rehabilitation projects (e.g. Matsui et al., 2010; Brown et al., 2014a). In addition, these projects generally attempt to produce a rough approximation of the surface elevation of a reference forest, and do not seek to improve rehabilitation success through use of predictive modelling to estimate the establishment of potential species.

This study examined the extent to which surface elevation influenced the establishment success of a 21.5 ha mangrove rehabilitation site in South Sulawesi, Indonesia. This was achieved through (i) mapping of surface elevation before and after rehabilitation works and, (ii) using species-specific elevation envelopes defined from a neighbouring reference forest to project potential areas within the rehabilitation site that were suitable for mangrove establishment. The study focused on surface elevation due to its general link to tidal inundation, and because it is a relatively cost-effective and straightforward variable for rehabilitation practitioners in the tropics to measure.

2. Materials and methods

2.1. Study area

The coastline of South Sulawesi, Indonesia, experiences a monsoonal climate. The northwest monsoon (December–March) is characterised by high precipitation and strong winds while the southeast monsoon (June–September) brings negligible rainfall (Visser et al., 2004). This coastline experiences a tidal range of 1.6 m with a mean tidal range of 0.95 m, with Mean High Water Spring at 1.33 m Chart Datum.

This study was conducted in three locations near the fishing villages of Kurri Caddi and Kurri Lompo (5° 01′ 57″ S, 119° 28′ 04″ E, Fig. 1). The main study site consists of 29 disused aquaculture ponds, covering 21.5 ha. Before rehabilitation, the ponds were used for semi-intensive farming of brackish water shrimp and milkfish polyculture. These ponds were created in the early 1980s and originally operated by a Korean venture. It was then bought and managed by the University of Muhammadiyah, Makassar (UNISMUH). In the past, neighbouring communities had no access or use rights in the ponds. However, after an agreement was reached between Mangrove Action Project – Indonesia (MAP-I) (now Blue Forests Indonesia), a non-governmental organisation (NGO), and UNISMUH, MAP-I was allowed to conduct rehabilitation works in the aquaculture ponds. The community now holds rights to access non-timber resources in some ponds and collaborate with MAP-I in participatory action research involving mangroves, aquaculture ponds and their own rice-fields. Interested members of the community are also involved in a multi-stakeholder working group involving academic, governmental and NGO partners, which serve to manage and advise mangrove rehabilitation.

The aquaculture ponds were surrounded by riverine and lower estuarine mangroves. Two reference forests, comprised solely of coastal and riverine greenbelts were surveyed (Fig. 1b). They are located 2.3 km and 0.05 km from the aquaculture ponds, and are approximately 200 m and 50 m wide respectively. Although only a subset of natural mangrove surface gradients and floral species were found at the reference forests, these sites nonetheless represented the best reference as more than 90% of mangroves in Maros and neighbouring Pangkep District have been converted to aquaculture.

2.2. Field data collection

2.2.1. Pre-rehabilitation mapping of abandoned aquaculture ponds

In September 2013, a Trimble Real Time Kinematic GPS (RTK-GPS) was used to establish nine elevation benchmarks throughout