The practice of hydrological restoration to rehabilitate abandoned shrimp ponds in Bunaken National Park, Northern Sulawesi, Indonesia

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Abstract. The world has lost a large extent of mangroves, while rates of recovery of these ecosystems from natural re-growth and restoration are slow. We developed a hydrological restoration technique to investigate the importance of hydrological modification in mangrove restoration success. Ecological Mangrove Restoration was adopted to restore abandoned shrimp ponds at Tiwoho, Bunaken National Park, Northern Sulawesi. Hydrological modification resulted in the creation of various mangrove sub-habitat conditions. These conditions remained unstable within the first three years and became relatively stable after seven years. Tidal inundation and soil surface salinity appeared to be the major factors controlling mangrove establishment and growth. All natural recruits and planted trees grew faster and produced more propagules/fruits within a short period of time after the normal physical conditions achieved. The restored site was covered by approximately 91.3 % of vegetation with the same canopy species composition as the natural stands. The practiced hydrological restoration method was simple, cost-effective and can help other practitioners in improving their mangrove restoration techniques.

Keywords: Hydrological restoration, mangrove, salinity, tidal inundation

INTRODUCTION

Mangroves are valuable coastal environments, provide biomass and contribute to productivity that is of substantial benefit to human populations, primarily fisheries and forestry products (Bandaranayake 1998). Other critical ecosystem services that mangroves provide include coastline protection, carbon storage, water quality enhancement and cultural services (Koch et al. 2009; Barbier 2012). The existence of mangroves has been chiefly relevant in terms of mitigation of climate change effects.

Apprehension about the extent of mangrove ecosystem loss has been declared in various publications (e.g. Spalding et al. 1997; Wolanski et al. 2000; Valiela et al. 2001; Duke et al. 2007). According to Valiela et al. (2001), the world has lost about 35% (47,346 km^2) mangrove since the 1980s with an estimated global loss of 2.1 % (2,834 km^2) per year during the second half of the 20th century. In the early 21st century, deforestation rates are thought to have reduced, the world loss of 1646 km^2 of mangroves from 2000 to 2012 (Hamilton and Casey 2016). Human pressure on mangroves has been summarized extensively in various journals and reports (e.g. UNEP 2014; Thomas et al. 2017; Feller et al. *In Press*), and the majority of mangrove loss has been attributed to human pressure, mostly aquaculture practices (Thomas et al. 2017).

The practice of mangrove restoration throughout the world has been described in various reports (e.g. Field 1999; Ellison 2000; Kairo 2001; Giesen et al. 2006; Biswas et al. 2007). Countries such as Bangladesh, Indonesia, the Philippines, and Vietnam stand out as the countries that have put the most effort into the rehabilitation of mangrove ecosystems (Field 1999). However, greatest mangrove restoration works in Southeast Asia have followed a trial and error method (Biswas et al. 2007). In China, the use of a single species in such rehabilitation programs reduced biodiversity of planted forests (Chen et al. 2009). Generally, rates of recovery from natural re-growth and restoration are slow (Lewis 2000; Sherman et al. 2000).

Rehabilitation of mangroves succeeds when the hydrological environment is suitable for mangrove growth (Lewis 2005; Howard et al. 2017). In the case of disused shrimp pond, there may be accelerated soil erosion, a decrease in soil water storage capacity, a depletion of soil organic matter, a reduction in the biodiversity of soil fauna, etc. (Field 1999). The Ecological Mangrove Restoration (EMR) (Lewis and Marshall 1997) was adopted to restore 15.2 hectares of abandoned shrimp ponds at Tiwoho, Bunaken National Park, Northern Sulawesi. The site provided a good example of physical alterations which disturbed the natural hydrology of a mangrove system, and had also undergone poor natural regeneration and numerous failed artificial planting efforts. Whereas, previous field observations found that healthy seedlings were produced regularly by trees of common species at the neighboring forests, and that past artificial plantations had followed proper procedures. In this research, we hypothesized that modification of the site hydrology would facilitate the creation of suitable environment for mangroves to grow. It was also hypothesized that the establishment of mangroves at restored site would depend on factors of tidal inundation level, texture and salinity of surface sediments, and that types of mangrove stands at restored site would be similar to types of natural mangrove stands at the neighboring forests. This paper reports the importance of hydrological modification in mangrove restoration success. Learning from this study site can help other practitioners improve their mangrove restoration techniques in order to achieve greater success worldwide.

MATERIALS AND METHODS

Site description

The restoration site is located at Tiwoho Village, Bunaken National Park, North Sulawesi, Indonesia between 01º35’00” – 01º36’2.00”N and 124º50’21.06” – 124º50’47’10”E (Figure 1). Approximately 15.2 hectares of mangrove area was converted into shrimp ponds in 1991 before it was abandoned in 1993. Since early 2000, effort to rehabilitate deprave mangrove areas at Tiwoho was initiated through a community-based mangrove management program.

Figure 1. Map of the restoration site at Tiwoho Village.

Hydrological restoration technique

The following six steps suggested by Lewis (2011), formerly five steps (Lewis and Marshall 1997), were adopted to conduct the process of hydrological restoration: (i) Step 1: understanding the reproduction pattern, successful propagule and seedling establishment. The reproduction cycle was investigated for seven commonly encountered mangrove species (*Avicennia marina, Bruguiera gymnorrhiza, Ceriops tagal, Lumnitzera littorea, Rhizophora apiculata, Rhizophora stylosa, Scyphyphora hydrophyllacea*) from November 2002 to October 2009 at every moment the site was visited (at least once a month). The parameters evaluated were the number of flowers and propagules produced by 25 marked trees of each species. The presence of propagules and seedlings over the floor within the abandoned shrimp ponds was also observed. (ii) Step 2: understanding the normal hydrology pattern. Field observations were conducted to check normal elevation and level of tidal inundation at the boundary of the restoration site where natural mangrove occurred (Profiles x – x’, y – y’ in Figure 2). The field observations were conducted by measuring level of tidal inundation at seaward margin, middle area and landward margin during early neap-tide, full moon-tide and late neap-tide. A pole gage was used to measure the level of tidal inundation. Freshwater influencing the restoration site was also observed. (iii) Step 3: assessing the modification of the previous mangrove environment that prevent natural secondary succession. Seawater circulation pattern, site elevation and tidal inundation were observed. The pattern of seawater circulation was observed visually during ebb and spring tides. Site elevation was described by means of a modified profiler – a tool equipped with protractor to measure the angle and length of slope for every 1 m distance along a topography profile. All sampling points for these observations can be seen in Figure 2. (iv) Step 4: selecting a restoration site. Community consultations were carried out to ensure that the site was secured from any threats, including the issues of land ownership, long-term access and conservation of the site. (v) Step 5: designing the restoration program to initially restore the appropriate hydrology. Data from seawater circulation pattern, level of tidal inundation and site elevation, from step 3 were analysed to develop a hydrological restoration plan for the targeted site. Physical work was conducted between November 2004 to February 2005. The west tidal canal was blocked at three points by means of concrete wall at the base and sand-sacks on the top (Figure 3 AB). The east canal was not blocked off because the canal had been shallow and its role in controlling the tidal circulation was not significant. A slight physical change was made to this canal by creating small tidal canals that connected to the main eastern canal to the unvegetated area (Figure 3 CD). In order to improve access of tidal water to enter areas within the five shrimp pond partitions, a number of small canals were created (Figure 3 EFGHIJ). (vi) Step 6: utilizing actual planting of propagules or seedlings only when natural recruitment will not provide the quantity of successfully established seedlings. In open areas where natural recruits were absent, seedlings of mostly *C. tagal* were planted because they are more tolerant to higher soil salinity condition. Seedlings of *R. apiculata* and *B. gymnorrhiza* were planted in locations where surface salinity less than 20 ppt. These artificial plantations were conducted in February 2005 when physical work was done.

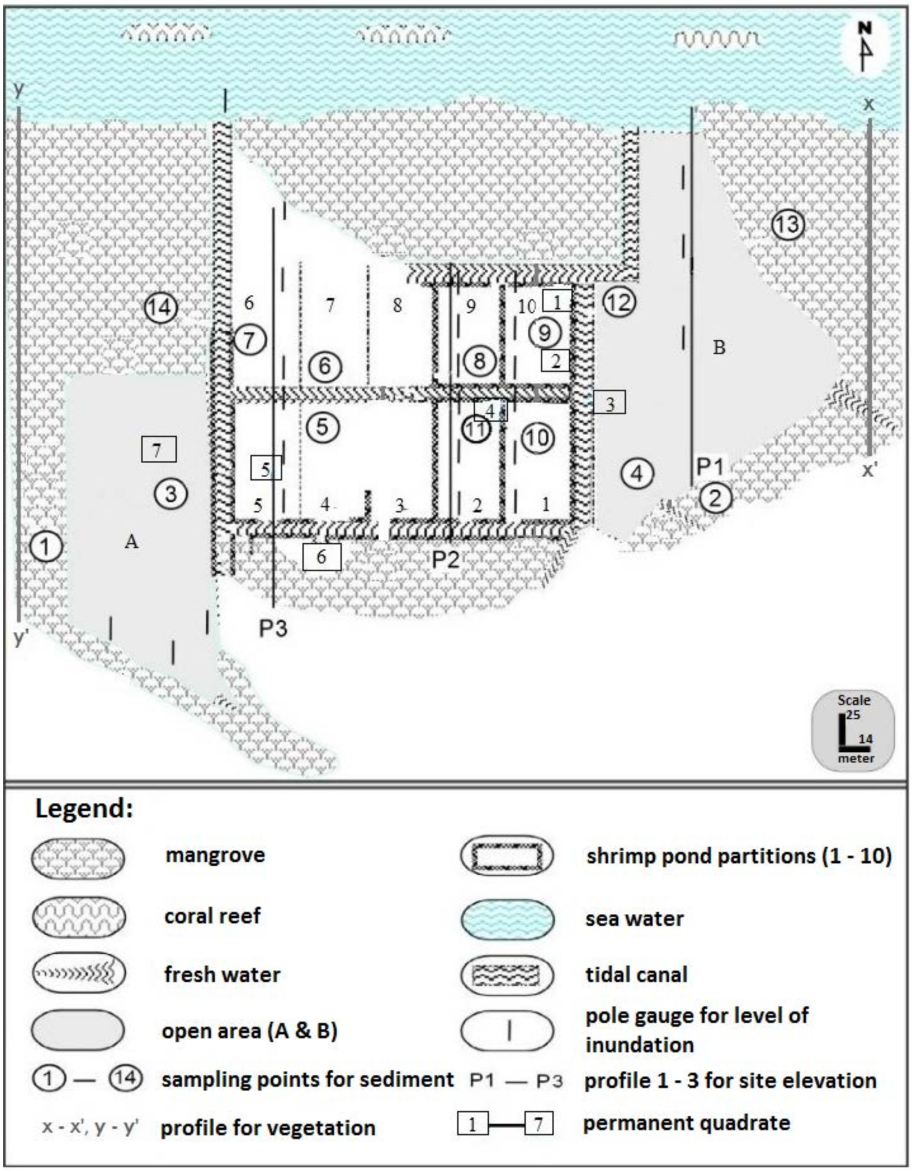

Figure 2. Observation points for physical assessment.

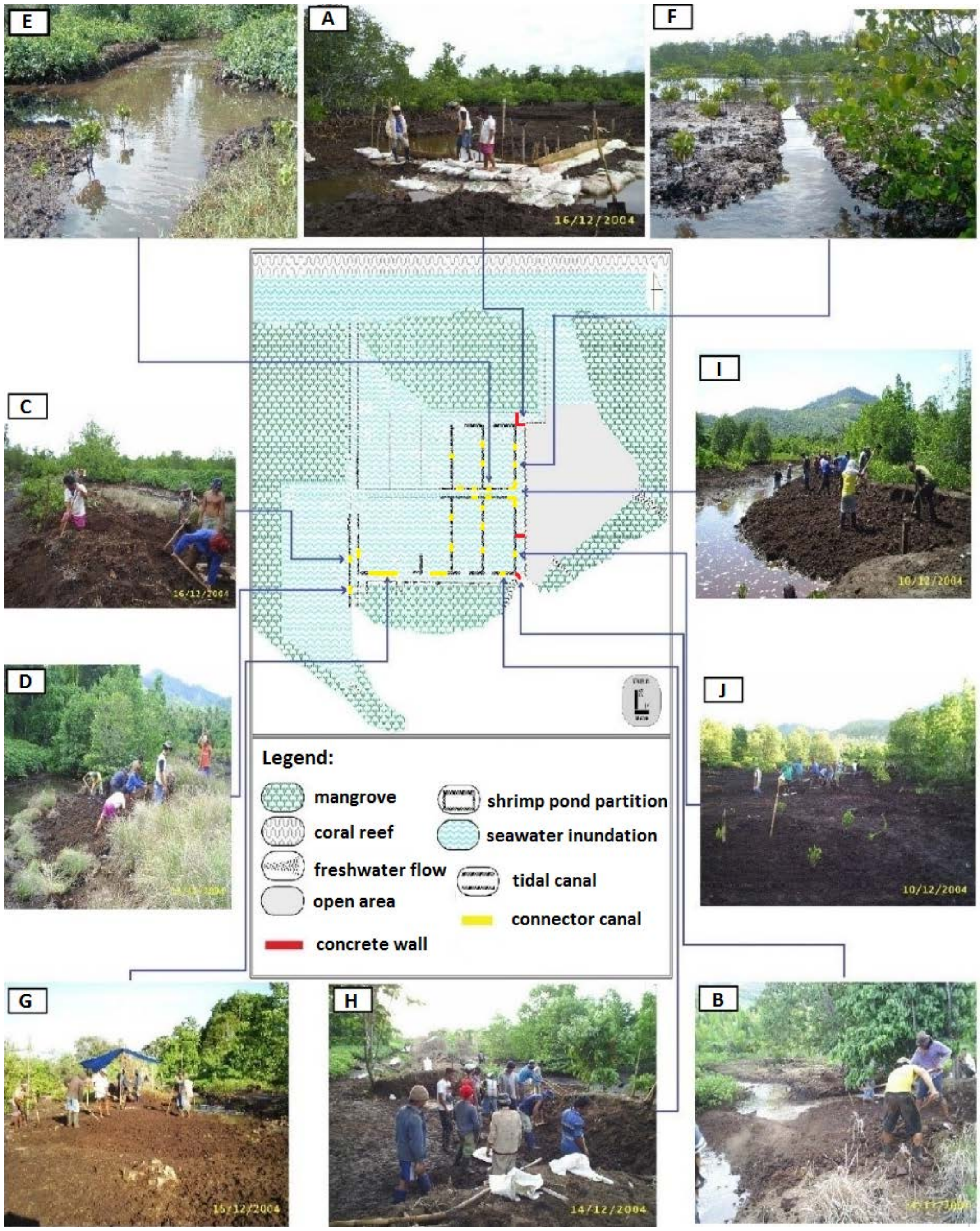

Figure 3. Physical changes to restore the hydrological condition.

In addition, twice a month during the first year the restoration site was checked for the presence of free moving mangrove logs as these could easily kill established mangrove seedlings. These logs were stabilized by tying up them to standing trees or stakes. The site was also controlled regularly from man-made disturbances.

Monitoring of mangrove seedlings establishment and survival

To monitor the recruitment of natural seedlings and their survival, seven permanent plots of 20 m^2 were established at different locations (Figure 2). The presence of mangrove seedlings were identified and counted at every three months from July 2006 to April 2007 and once a year from December 2007 to October 2010. During the observation notes were made about dying seedlings and possible causes of death. General observations were also conducted at specific locations where new mangrove seedlings were observable.

Assessment of mangrove community structure

Species composition, stem density and above ground biomass were assessed to describe general conditions of the neighboring mangrove community. Field determination of the flora were confirmed by a range of systematic reviews (e.g.

Ding Hou, 1958; Tomlinson 1986; Noor et al. 2006). Measurements of stem density were made in contiguous quadrats of 10 m^2 placed along transects indicated as x – x', y – y' (Figure 2). Above ground biomass was calculated using the common equation developed by Komiyama et al. (2005). Biodiversity Professional Version 2.0 (McAleece et al. 1997) was used to group community associations.

Vegetation cover analysis

Map of Peta Rupabumi Indonesia 1991 (Bakosurtanal 1991) was used for visualization, and Google Earth Pro images date 2003, 2011, and 2016 provided by Digital Globe were selected for vegetation cover analysis. Downloaded images were geometrically corrected to fix geographical projection and real position in the field. Global Mapper 11 was used to conduct the correction and on-screen digitizing was applied to analyze vegetation cover.

Assessment of surface soil texture and salinity

Surface soil samples were taken from 14 nominal locations (Figure 2) representing open area at landward position (sampling no. 3 and 4), open area at middle position (sampling no. 12), area of broken shrimp pond construction (sampling no. 5, 6 and 7), area of good shrimp ponds construction (sampling no. 8, 9, 10 and 11), and area with vegetation for control at landward position (sampling no. 1 and 2) and at middle position (sampling no. 13 and 14). Samples were taken at 0 – 300 mm depth at five random points in every location and pooled prior to laboratory analysis. Soil texture was determined using the pipette method (Olmstead et al. 1930). Textural classes were classified using the textural triangle of USDA (United States Department of Agriculture). Soil salinity was measured using a Hand Refractometer (ATAGO S/ MILL) of water samples of a known volume eluted through sediment samples. Samples were collected twice to asses changes, first in 2003 (before restoration) and second in 2005 (after restoration).

RESULTS AND DISCUSSION

Hydrological changes

Three transects were set up across the restoration site to evaluate the site elevation before the site was physicaly restored, and the results are presented in Figure 4. Profile 1 depicts a transect located across the open area to the west where trees in this location had been cut clear in 1992. From land to the sea the topography increased slighly up to 1 m at the distance of 150 m before decreasing slighly. Profile 2 describs a transect located across shrimp pond partitions number 2 and 9, along a distance of about 200 m. The topography decreased sharply from the land towards the sea with significant barriers of high dike walls. Profile 3 describes the topography along a transect that was located across shrimp pond partitions number 5 and 6. The elevation was relatively flat and the area within shrimp pond partition number 5 remained higher.

Before the site was physically restored, the presence of deeper tidal channels to the west and to the east, secondary tidal channels in about the middle part and near the landward margin of the restoration site played a significant role in the distribution of tidal waters. During the flood-tide seawater entered firstly the tidal channels and at certain level it started to distribute to the shallow areas at shrimp pond partition number 9 and 10, proceeded to partition number 6 to 8. Depending upon the level of tide, the shrimp pond partition number 1 and 2 flooded lately because the presence of higher dikes. Because the topography of open areas number 1 and 2 were relatively higher, these two areas flooded at the high tide level. During the ebb-tide seawater leaved the restoration site through similar patches that they came, but the shallow areas within shrimp pond partition number 1, 2, 9 and 10 remained wet at lower tide level. Variation in level of inundation over the restoration site had been quantified for different level of tide periods. Open area 1 and 2 and shrimp pond partition number 1 and 2 were inundated only at high tide level during the period of full-moon. All others shrimp pond partitions were inundated during early neap-tide and late neap-tide periods with the higher seawater level at area around shrimp pond number 6 and the lowest seawater level at the area around shrimp pond number 5. At all tide periods seawater level seemed to be slightly different at shrimp pond partitions number 9 and 10.

Two conditions have to be achieved in order to bring the changed hydrological patterns to the relatively normal hydrological condition. The first was that high soil condition in open area had to be reduced. The second was the tidal water circulation and level of inundation had to be made close to the previous condition before the construction of shrimp ponds. Ideally, to achieve both conditions all tidal channels had to be closed off and all dikes between shrimp pond partitions had to be broken up. However, the ideal efforts could not be made due to both resource constraints and the presence of young natural trees established as well as a grove of planted, stunted *C. tagal*. It was decided that strategic dike wall breaching, creation of natural tidal channels, and blockage of some artificial channels could effectively restore the area with minimum budget and disturbance of current vegetation.

Tidal circulation patterns changed after the site was physically restored. Incoming seawater usually flowing through the east canal was retained by the seaward wall. When the water level had reached the height of the wall, seawater started to flow in at normal condition, submerging the restoration area homogenously and gradually rising up to the maximum level of tide. During the ebb-tide seawater flowed out from the restoration site through the same pathways of incoming seawater.

At low seawater level, the east canal remained inundated, the loss of freshwater from the restoration site could be minimized, and none of the remaining five shrimp pond partitions were inundated.

Effect of hydrological change on soil condition

Fourteen surface soil samples representing six major types of sampling locations were analyzed to evaluate the composition of sand, silt and clay, and the result from samples collected in 2003 (before restoration) is summarized in Figure 5. Using the textural classes of USDA, the six sampling locations could be categorized into two classes of clay loam and silty clay loam. The textural class of clay loam occurred at three locations of type A (area with vegetation at landward margin), type C (remaining shrimp pond partitions number 4, 6, 7), and type E (open area near the tidal channel to the west). Meanwhile, sampling location type B (open areas near landward margin), type D (areas within shrimp pond partitions number 1, 2, 9, 10), and type F (areas with vegetation at about the middle zone), were all classified into silty clay loam.

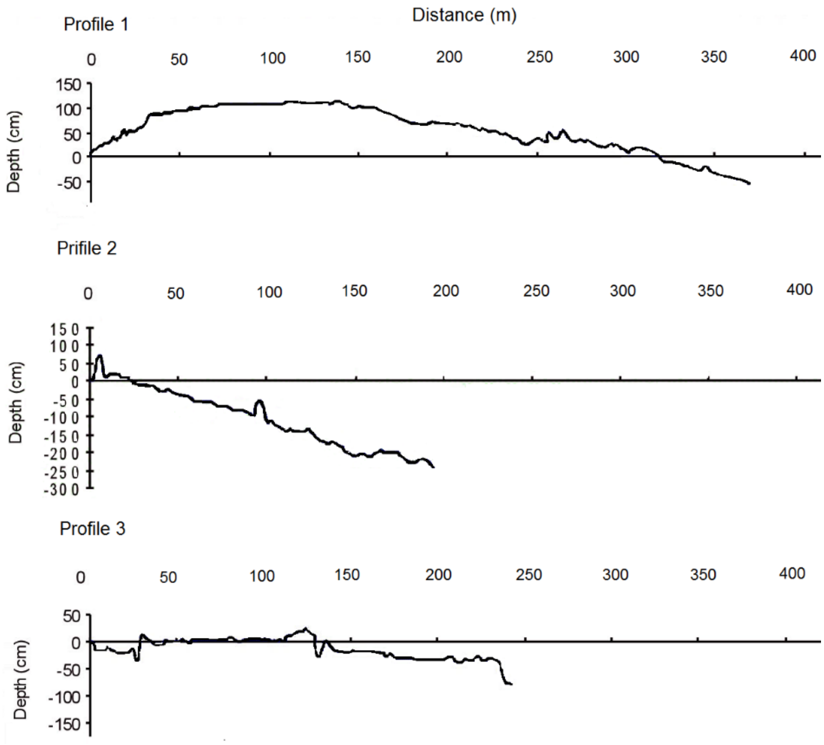

Figure 4. Topography of the restoration site (profiles 1 – 3 as in Figure 2).

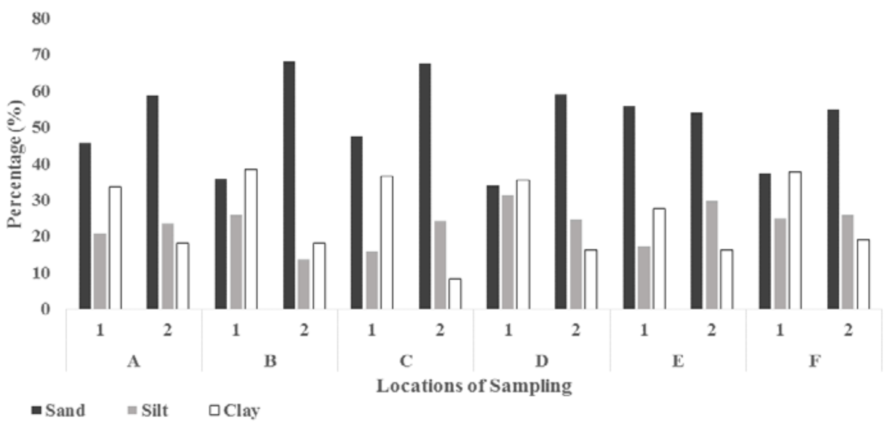

Figure 5. Sediment composition over the six sampling locations in 2003 (1, before restoration) and in 2005 (2, after restoration) indicated in Figure 2 (A sampling number 1,2; B number 3, 4; C number 5 - 7; D number 8 – 11; E number 12; F number 13, 14).

The change in hydrological condition resulted in the new formation of surface soil texture and the salinity. In 2005 an analysis of fourteen surface soil samples indicated that soil texture at the seaward margin area was categorized as sandy clay texture. At the middle area within the shrimp pond partitions the soil texture was classified into three different texture of sandy clay, sandy clay loam, and silty clay loam. At the middle area with no vegetation there were clay loam, sandy clay loam, and sandy clay textures, while the area with vegetation had clay loam texture. The landward margin area with no vegetation had a textural class of clay loam, comparing to sandy clay loam and clay loam at the area with vegetation. Surface soil salinity in open area at middle zone ranged from 19 to 21 ppt. Meanwhile, some locations at the middle and landward zones that were influenced by freshwater, the salinity was relatively lower, varying from 8 to 12 ppt.

Natural seedlings availability and establishment within restoration sites

Reproduction pattern of seven commonly encountered mangrove species in the neighboring mangrove forest and successful propagule and seedling establishment were investigated. During observation from 2002 – 2009, all species growing in the neighboring forests produced flowers, fruits or propagules more than once a year in various quantity. *Ceriops tagal* produced flowers most frequently, followed by *R. apiculata*, *B. gymnorrhiza* dan *S. alba.* Flowering peak season for most species occurred between November and May. Short periods of flowering and continuous presence of fruits on stems of *C. tagal* and *R. apiculata* indicated continuous pollination. Before the site being restored, propagules of *B. gymnorrhiza*, *C. tagal* and *R. apiculata* were rarely found in open areas. Small numbers of seedlings and saplings of *R. apiculata* occurred at certain locations within shrimp ponds. New recruitments of *A. marina* and *S. alba* were also found on specific locations within shrimp ponds, but they were not abundant.

Natural seedlings of *A. marina* and *S. alba* appeared on flats three months after hydrological restoration, but they were not able to survive. Observation on natural recruits and their survival within the fourteen permanent plots was conducted from 2006 to 2010, and the results are presented in Figure 6. Four species of *A. marina*, *B. gymnorrhiza*, *R. apiculata* and *S. alba* were successfully established in the permanent plots. The number of seedlings of *R. apiculata* and *S. alba* increased gradually by the year 2008 then slowly increased in the years after. The trend was different from seedlings of *A. marina* and *B. gymnorrhiza*. The number of seedlings of *A. marina* increased slowly by 2008 and then disappeared. Meanwhile, the number of seedlings of *B. gymnorrhiza* increased slowly by 2007 and decreased after that.

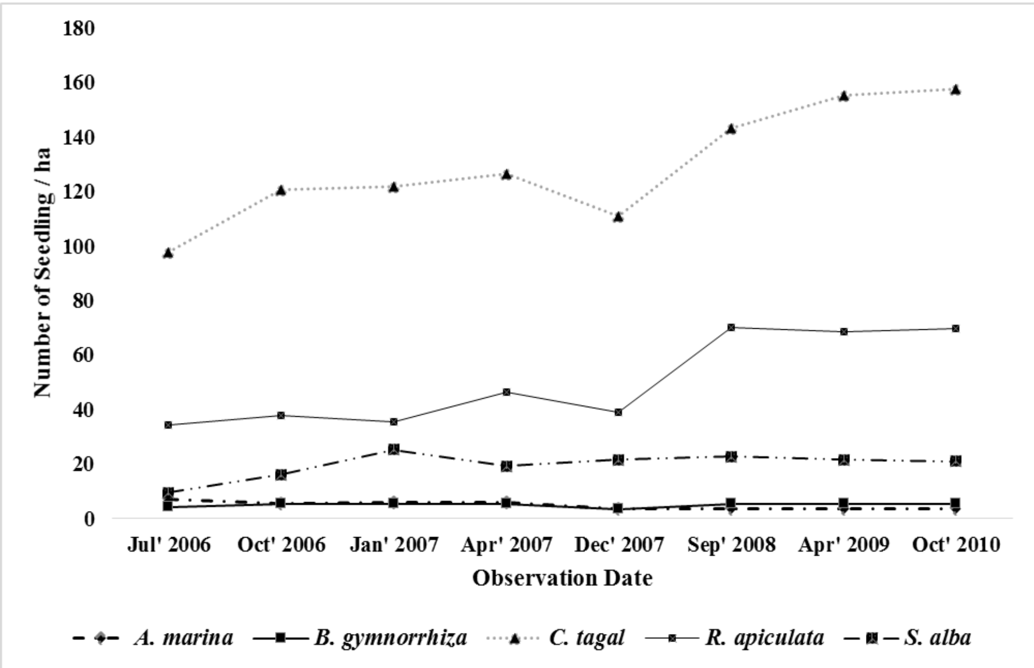

Figure 6. The number of seedlings from July 2006 to October 2010.

The natural mangrove community and stands development within the restored site

Out of 32 mangrove species listed by Tomlinson (1986), 15 species were identified in the studied area. They included seven common canopy species, namely *A. marina*, *B. gymnorrhiza*, *C. tagal*, *R. apiculata*, *R. stylosa*, *S. alba*, and *S. hydrophyllacea*. *Nypa fruticans* occurred only at sites with regular supply of freshwater. A single specimen of *Sonneratia ovata* was noted at a landward site with regular freshwater input. Other uncommon species included: *Acanthus ilicifolius*, *Acrosticum aureum*, *Aegiceras corniculatum*, *Ceriops zippeliana*, *Heritiera littoralis*, *Lumnitzera littorea.*

Five community types were noted in the the neighboring forests: (1) Community Type I, consisted of stands of *R. apiculata*, *R. stylosa*, and *S. alba*, (2) Community Type II, was formed by stands of *R. apiculata* and *S. alba* with a small number of *B. gymnorrhiza*, (3) Community Type III, characterized by the monospecific dominance of old *R. apiculata* indicated by top-dying branches, (4) Community Type IV, occurred at lower elevations with a mixed dominant canopy of

R. apiculata and *C. tagal*, (5) Community Type V, was dominated by mono-stand of *C. tagal* occurring at slightly higher elevations towards the hinterland fringe, and characterized by dense populations and stunted growth. Profile diagrams of the mangrove communities and their relative spatial distribution are presented in Figure 7.

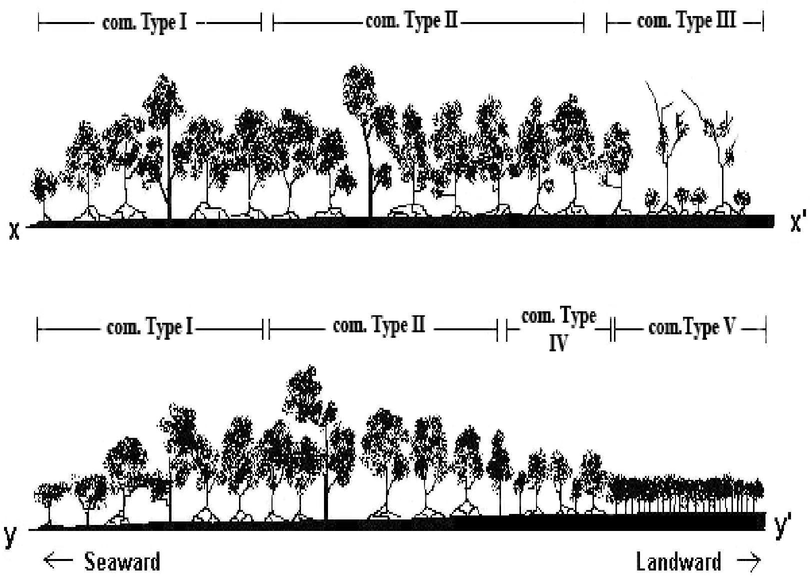

Figure 7. Profile diagrams of the recognized communities along transects x–x’ and y–y’ as indicated in Figure 2.

Stem density and biomass varied among community types. The lowest stem density was 52 trees ha^{-1} for Community Type III with a total biomass of 44.9 ton ha^{-1}. Community Types I and II exhibited relatively higher biomass values of 108.0 ton ha^{-1}/ha and 136.0 ton ha^{-1}, and stem densities of 186 trees ha^{-1} and 303 trees ha^{-1} respectively. Although stem densities in Community Types IV and V were higher, 500 trees ha^{-1} and 1400 trees ha^{-1}, their relative biomass values were lower at 23.0 ton ha^{-1} and 9.6 ton ha^{-1} respectively.

Figure 8 represents the development of vegetation over time. In Figure 8 (A), natural recruits of *A. marina* had been established and formed a young dense population at the landward area near the tidal canal. In Figure 8 (B) planted seedlings and young trees of *R. apiculata* and *B. gymnorrhiza* had been established at open area near the concrete wall of the west tidal canal. In Figure 8 (C) early stunted growth of planted seedlings of *C. tagal* and natural recruits of *R. apiculata* indicated of fast and healthy growth. Figure 8 (D) represents successful growth and development of seedlings of mostly *C. tagal* that were planted after the site being restored, as well as natural recruits of the same species and *R. apiculata*. As indicated in the satellite images (Figure 9), the restoration sites had been covered by 91.3 % of vegetation in 2016 comparing to 24.8 % in 2003.

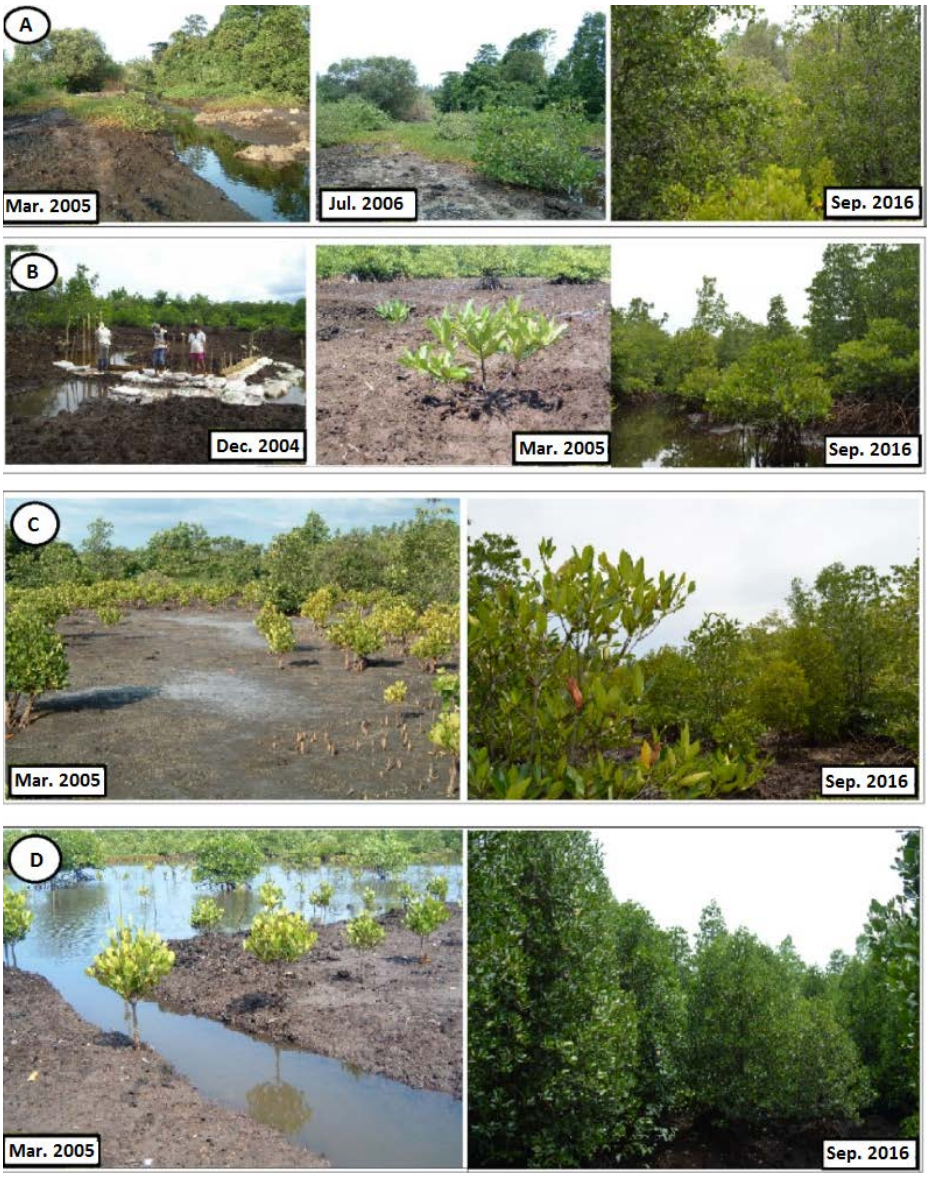

Figure 8. Development stages: (A) *A. marina*, (B) *R. apiculata* and *B. gymnorrhiza*, (C,D) *C. tagal* and *R. apiculata.*

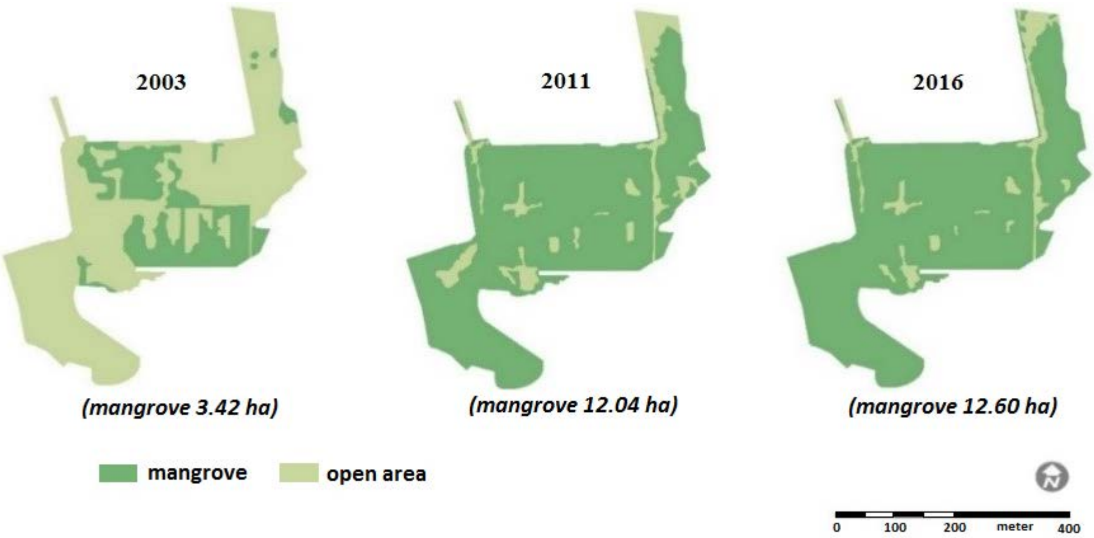

Figure 9. Map of vegetation cover in 2003, 2011, and 2016.

The significance of hydrological restoration

When physical assessment was conducted in 2002, the construction of shrimp ponds and other supporting physical infrastructure such as tidal canals has resulted in the change of the hydrological pattern of the area. This change altered the physical conditions relating to the level of tidal inundation, soil composition and texture, as well as the gradients of surface soil salinity. In comparison to the condition of ten mangrove sub-habitats identified in Bunaken National Park (Djamaluddin 2004, 2018), the two factors of tidal inundation and soil composition and texture seemed to be unusual, while the gradients of soil surface salinity appeared to be higher at certain locations. Most of these physical conditions prevented the natural establishment and growth of mangrove species.

The main objective of the restoration program was to create a variety of suitable habitats for mangrove species. As the west tidal canal had been blocked at certain locations and shrimp pond partitions had been breached to improve access of seawater and freshwater, there was significant change in the hydrology of the restoration site. It was predicted that in the beginning the surface soil salinity would remain high in the open area due to excessive evaporation, which would decrease slightly over time as the planted seedlings (mostly *C. tagal*) and natural recruits began to grow. In most of the restoration areas, the restoration of hydrology resulted in the relatively normal levels of tidal inundation and redistribution of surface sediments. All of the four major shrimp pond partitions were inundated during the ebb-tide, and the structure of surface sediments became more stable.

In the early stage of development, rapid growth of dense mangrove populations that was dominated by *R. apiculata* at seaward side of the restoration area influenced much on reducing the velocity of tidal water flowing into this area. This resulted in the more stable surface soil structure. In the contrary, early stage of development of planted seedlings (mostly *C. tagal*) in open areas within the restoration site tended to grow slowly, probably because of the soil surface salinity within the area was high. It was predicted that the surface soil salinity at these areas would reach its relatively normal condition after seven years being restored. This relatively normal level of surface soil salinity was much influenced by the increase of canopy cover in these areas.

Stand development processes

The process of mangrove colonization, establishment, growth and development in the restoration site helps reinforce restoration strategy aimed at re-colonizing the intertidal habitat. The process appears to be dynamic where each species has its own strategy to exploit newly available habitat (eg., Duke et al. 1998; Tomlinson and Cox 2000; Shi et al. 2005; Villocino et al. 2015). Long-term observation of the process also helps describe key environmental factors that control the establishment of mangrove species and competition between them that eventuate the future structure of the mangrove forest. Figure 10 summarizes the development stages of mangrove communities in relation to changes in habitat condition over 12 years of observation.

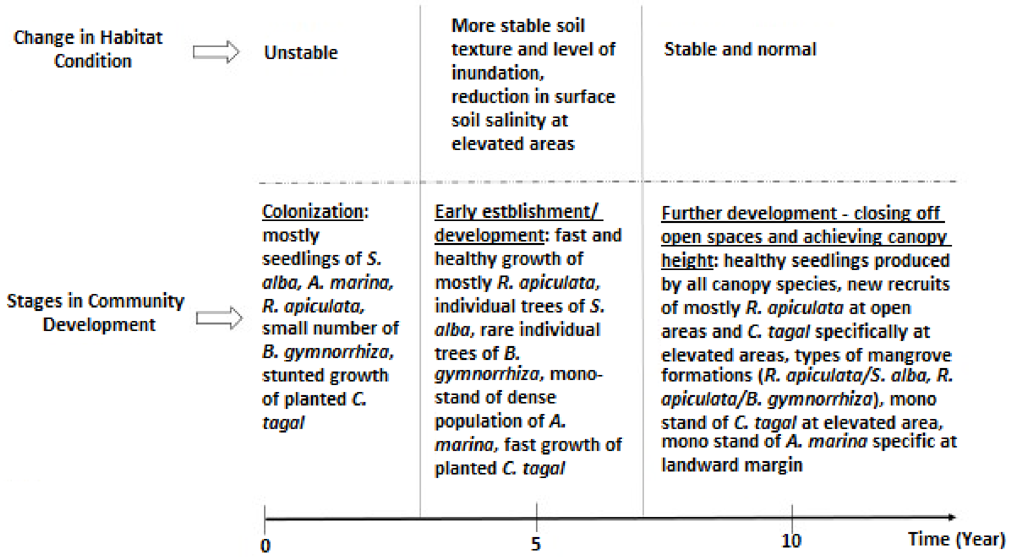

Figure 10. Development stages of mangrove communities over 12 years observation.

In the beginning of the process where the physical condition of the environment remained unstable, seedlings of *A. marina* and *S. alba* took advantage of this condition and started to colonize open areas within the restoration sites with the exception for the area where soil surface salinity remained high. Because the physical conditions of the environment remained unstable for certain period of time that was expected to last for the previous three years, most seedlings of *S. alba* did not survive. This fact may explain how physical environmental factors control the early stage establishment of *S. alba*. According to Balke et al. (2013) sediment disturbance with additional stressors of inundation and water movement may reduce the survival of *S. alba* seedlings. In comparison, new arrivals of usually dense seedlings of *A. marina* quickly become established and grown in a suitable condition. Meanwhile, individual seedlings of the same species failed to survive at other locations probably due to prolonged salinity stress than may affect photosynthesis of these seedlings (Yan et al. 2007). The significant difference between both species in the early stage of establishment was that seedlings of *A. marina* were suitable for landward area where soil salinity could be higher than areas of established seedlings of *S. alba*.

In the early stage of establishment new recruits of *R. apiculata* experienced problems colonizing the relatively unstable condition, and almost half of them died. Seedlings of this species were not able to colonize an open-elevated site where the soil salinity remained higher. A small number of seedlings of *B. gymnorrhiza* also experienced problem at this stage, and most of them died within the first three years. Waterlogging is the most likely factor that affects the early establishment of this species (Ye et al. 2003). This fact also explained clearly why species of *B. gymnorrhiza* were rarely found in mono-stand community of the mangrove forest in the region (Djamaluddin 2004, 2015).

When the physical conditions of the restoration site became more stable by the third year, surviving seedlings of *R. apiculata* grew fast and formed closed-canopy stands within open areas of the restoration sites. At this stage, individual young trees of *S. alba* competed with the fast growing young trees of *R. apiculata* to reach the canopy height. New arrivals of mangrove species had been rare and seedlings of 1 to 2 years old died probably due to limitation in light intensity on the forest floor. At several locations, planted trees of *R. apiculata* and *C. tagal* also grew faster and reached canopy height that was similar to canopy height of natural young trees of *R. apiculata*. At elevated areas, previously stunted growth of planted seedlings dominated by *C. tagal* seemed to be healthier with more branches. It was predicted that the growth rate of trees at these areas influenced much by the level of surface soil salinity. The lesser the level of soil surface the more healthy the trees, but a sudden major shift in salinity can kill seedlings and saplings of this species (Aziz and Khan 2001).

Observations from September 2016 (time zero + 11.5 years), revealed a relatively stable soil condition and normalized level of inundation. Healthy propagules of *R. apiculata* and fruits of *S. alba* were abundant. As the canopy cover increased it was expected that seedlings of *R. apiculata* were suitable to establish on the remaining open spaces within the site. At more elevated areas nearby landward margin planted young trees dominated by *C. tagal* also started to produce more healthy propagules and seedlings were common. At this stage, the forest development dynamic consisted of two processes of colonizing or closing off open spaces and achieving of the canopy height.

The end process of community development is predictable. There will not be new mangrove species as a main feature of the future structure of the mangrove forest within the restoration sites. At the middle zone and seaward margin the continued formation of *R. apiculata* and *S. alba* in the canopy will result in natural mangrove communities of types I and II described above. At the landward margin of elevated areas *C. tagal* will form a dominant stand similar to the natural Community Type V. Individual trees of *B. gymnorrhiza* will occur specifically at the middle zone where *R. apiculata* trees would be dominant in the canopy and mono-stands of *A. marina* will dominate at specific sites in the landward margin. These last two types of community were also identified to be common over the mangroves of Bunaken National Park (Djamaluddin 2004).

In conclusion, the modification of the site hydrology has changed the physical conditions of restored sites. Two factors of tidal inundation and surface soil salinity appeared to be the major factors that controlled the mangrove species establishment and growth. By seven years, these two factors appeared to be relatively normal. Although the current achievement of establishment is in the stage towards early development where young trees grow faster and more seedlings are produced by the canopy species, the future process of forest development is predicted to be naturally stable with no changes in the composition of canopy species that is the same as natural stands. All applied procedures were simple and cost-effective, and the results were significantly successful. These can be adopted and adapted to rehabilitate abandoned shrimp ponds and others disturbed mangrove areas.

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