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Estuarine, Coastal and Shelf Science

DOI:
10.1016/j.ecss.2019.04.003

Published: 30/06/2019

Peer reviewed version

Mangrove Area and Propagule Number Planting Targets Produce Sub-Optimal Rehabilitation and Afforestation Outcomes

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Academic Editors: Dr Tim Jennerjahn and Dr Martin Zimmer

ABSTRACT

Mangrove rehabilitation projects often fail completely or fail to meet their objectives. This study examines village-level rehabilitation planting carried out in 13 villages (119 rehabilitation attempts at 74 sites) across two countries in southeast Asia, to assess village-level rehabilitation effectiveness, and to identify what factors influenced outcomes. Mean propagule survival across all rehabilitation attempts was 20% with a median of 10%. Sixty six percent of attempts had a survival rate of less than 20%. Mid mangrove zone projects were more successful (mean 30%) than rehabilitation projects at other elevations. Planting on mudflats, representing 32% of rehabilitation / afforestation attempts, achieved only a 1.4% propagule survival rate. The overall low success rate was due to several inter-related factors. Poor site/species matching on high and low elevation sites was common; for example, *Rhizophora* spp. was used alone or in combination at least 65% of the time, including on mudflats where this genus is ecologically unlikely to establish. Site selection was often driven by the desire to achieve centrally defined area or propagule *planting* targets, rather than *survivorship* targets, and thus required large, uncontested project areas. Conversely, the presence of natural regeneration, even if in small amounts, was associated with higher than average success. Therefore, it was estimated that only 16% of planting attempts were actually necessary.

Highlights

- Mean survival of all mangrove rehabilitation planting attempts was 20%, median 10%
- Only 16% of planting attempts deemed necessary vs. natural recruitment potential
- Better hydrological connection significantly improved survivorship (mid/high zones)
- Area or propagule planting targets should be changed to survivorship targets

Keywords: mangrove restoration, mangroves, failure, survivorship, area target, planting target, Thailand, Philippines

1. Introduction

1.1 Mangroves are Particularly Beneficial to the Poorest Coastal Villagers

Mangroves form highly productive ecosystems, (Alongi, 2009) which provide many direct and indirect benefits and services (Moberg and Rönnbäck, 2003; Saenger, 2002; van Oudenhoven et al., 2015). These services are particularly valuable and relevant to the poorest members of coastal villages (Glaser and da Silva Oliveira, 2004; Kairo et al., 2001; Springate-Baginski and Than, 2011; Stevenson et al., 1999; Sunderlin et al., 2005). They include a nursery function for fish and shrimp (Saenger et al., 2013; Salmo III et al., 2018) and provision of wood for construction and fuel for cooking (Moberg and Rönnbäck, 2003).

1.2 Mangrove Losses Declining, but Measurement is Challenging

In previous decades, management of mangrove loss has proved challenging. This was as a result of low-resolution remote sensing imagery and of classifying mangrove as opposed to other types of vegetation. Furthermore, there has been a lack of a definitive methodology for identifying and classifying ‘mangrove’ at different levels of degradation and canopy cover (Giri et al., 2011; Hamilton and Casey, 2016). Within the 21st century, global losses have been reported to be 0.16% - 0.39% per year, indicating a slowing of the rate of loss from the 1980s (0.99%) and 1990s (0.7%) (Hamilton and Casey, 2016).

Southeast Asia has historically seen some of the greatest losses. For example, mangrove cover in the Philippines has fallen from 450,000 ha in 1900 to 120,000 ha in 1995 but the rate of loss has slowed to 0.1% per year since 2000 (Long et al., 2014; Primavera and Esteban, 2008). In Thailand, using 1961 as a baseline, less than half of all the mangroves remain (Aksornkoae, 2004). From 2000 - 2012, Thai losses were 0.69% per year (Hamilton and Casey, 2016).

1.3 Mangrove Rehabilitation Initiated for Many Reasons and by a Variety of Actors

Following natural disasters such as the Indian Ocean tsunami of 2004 and cyclone Haiyan / Yolanda in the Philippines, and to recover some of the goods and services provided by mangroves, there have been significant efforts to rehabilitate areas of converted or degraded mangroves (Aung et al., 2011; Primavera et al., 2011; Primavera and Esteban, 2008). This effort has included attempts to afforest new areas that were previously not inhabited by mangroves. Most often, governments have commissioned mangrove rehabilitation programs through forestry and environment departments, which in turn have sometimes engaged local villages to assist. Occasionally, communities and villages have initiated their own rehabilitation projects. Examples include Pred Nai in Thailand (Fisher, 2000; Senyk, 2005) and Myanmar (Springate-Baginski and Than, 2011). There are also reports of rehabilitation by individuals within coastal villages, in the Philippines (Walters, 2004, 2000, 1997; Walters et al., 2005) and Thailand (pers. obs.).

1.4 'Restoration' or 'Rehabilitation'?

The scientific literature often uses 'restoration' and 'rehabilitation' interchangeably (van Oudenhoven et al., 2015) or uses other words including repair, reclamation, reforestation, conservation, afforestation or eco-development (Duke, 1996). Restoration might be defined as recovering an area back to an assumed original 'pristine' ecosystem, implicitly including the restoration of mangrove functionality (Kairo et al., 2001; Stevenson et al., 1999; Walters et al., 2008). However, the word is often used more broadly (McDonald et al., 2016). Rehabilitation is an attempt to recover *some* of the ecosystem functions or to find another stable use for the land (McDonald et al., 2016; Stevenson et al., 1999; Walters, 2008; but see Field, 1999a). The debate concerning these terms continues (see Dale et al., 2014 for a review). While acknowledging this debate, and the need for clarity of definition for legal purposes and for setting expectations (Dale et al., 2014), this paper will use the term rehabilitation. Similarly, care is needed when describing areas as 'degraded', because the perception of whether an area is partially degraded or not is affected by cultural expectation and land management intensity (Hobbs, 2016). Furthermore, changes to an ecosystem's state may be adjustments beyond those caused by normal forest growth and development processes, leading to a new equilibrium as a result of climate change or long-term variation of weather patterns (Hobbs, 2016; Mansourian et al., 2017).

1.5 What is 'Successful' Rehabilitation?

In principle project outcomes should be assessed in relation to stated project objectives, and this is crucial in the planning of any mangrove rehabilitation work (Field, 1999b; Lewis, 2000; Saenger, 2002). When viewing rehabilitation outcomes from a narrow standpoint, 'success' may be claimed after five to seven years, because this indicates probable long-term survivorship (i.e. to reproductive maturity) and eventual (re)establishment of a mangrove stand (Bosire et al., 2008; Kodikara et al., 2017). Salmo III et al., (2013) focused on vegetation and soil parameters in a study of monospecific plantations. Their study suggested that mangrove ecosystem stability might be reached by 11 years, and that ecological characteristics resembled natural mangroves after 25 years. Other indicators of success have focused on the whole ecosystem and consider that success can be claimed when the hydrological normality of a mangrove has returned (Asaeda et al., 2016). Alternatively rehabilitation assessment might compare project sites to natural mangroves (McDonald et al., 2016) but not in terms of succession (Ellison, 2000). Despite sometimes being an appropriate long-term measure, comparing project sites to old-growth mangroves is particularly difficult in countries such as Thailand and the Philippines. This is because much of the natural mangroves have been cut-over for charcoal or fuelwood and replanted with a less diverse range of species (Alongi, 2002). Resources permitting, a more comprehensive approach is an *ecological rehabilitation* perspective (the literature often uses *restoration* in this case) (Asaeda et al., 2016; Ellison, 2000; Lewis, 2005; Walters et al., 2008). This approach looks for the return of full ecosystem function, including outflow of organic material to, and habitat connectivity with, linked seagrass and coral systems. This can be relatively complete within five years (Saenger et al., 2013).

While social factors are pertinent, here we focus on a strictly biological (or silvicultural) definition of success – whether planted seeds / propagules survive to establishment.

1.6 Rehabilitation and Afforestation Successes and Failures

There have been positive mangrove afforestation survivorship outcomes in Bangladesh (Saenger and Siddiqi, 1993, but see Moberg and Rönnbäck, 2003) and successful mangrove rehabilitation in Florida (Brockmeyer et al., 1996; Lewis, 2005; Lewis and Gilmore, 2007), Philippines (Asaeda et al., 2016; Primavera et al., 2012; Walters, 2004) Indonesia, (Lewis and Brown, 2014) and Myanmar (pers. obs.). However, many rehabilitation projects fail completely or do not achieve their objectives (Elliott et al., 2016; Erftemeijer and Lewis, 1999; Field, 1996; IUCN, 2017;

Lewis, 2005; UNEP, 2007) or at best produce limited positive results (Alongi, 2002; Aung et al., 2011; Barbier, 2006; Ellison, 2000; Memon and Chandio, 2011; Moberg and Rönnbäck, 2003). Mangrove rehabilitation projects that have become established often resemble even-age class, mono-specific plantations rather than natural mangrove (Bosire et al., 2006; Ellison, 2000; Field, 1996; Lewis, 2005), bearing little or no similarity to the original mangrove (Alongi, 2002). In addition they exhibit only limited species zoning and biodiversity (Bosire et al., 2008). However, of greater immediate concern are the often extremely low propagule survival rates of these rehabilitation programs.

Sanyal (1998) reported that in West Bengal more than 9,000 ha were planted with only 1.5% probable survival. In the Philippines, despite significant efforts and financial inputs over the last twenty years, survival of planted mangroves remains low at 10-20% (Primavera, 2015; Primavera and Esteban, 2008; Samson and Rollon, 2008; Walters, 1997). Similar conclusions have been drawn from Sri Lankan rehabilitation programs (Samarakoon, 2012).

1.7 Technical Reasons for Previous Failures

Why do so many rehabilitation projects fail? Here we consider the suggestion that the most common technical reason for planting failure is poor site/species matching, i.e. choosing an unsuitable species to plant for a given site (Aung et al., 2011; Bosire et al., 2006; Lewis et al., 2016; Primavera and Esteban, 2008; Walters et al., 2008). What is meant by unsuitable? Individual species have differing tolerances to specific biogeochemical factors and gradients present across the intertidal area (Saenger, 2002). These include salinity, soil type, soil anoxia, sulphate levels, nutrient levels, pH, wave energy, temperature, light levels, inundation regimes (Alongi, 2009;

Tomlinson, 2016; van Loon et al., 2016), tides and wind distribution of propagules and seeds (van der Stocken et al., 2012), and species-selective predation by herbivores (Elster, 2000; Sousa et al., 2003). Species therefore exhibit differing ‘preferences’ for elevation and location within the intertidal zone (Duke, 2006; Snedaker, 1982; Tomlinson, 2016).

Closely related to site/species matching is poor site choice. Insufficient regard is often given to understanding local hydrology, topography relative to sea level, and the effects these have on soil conditions. These features greatly affect planting outcomes (Aung et al., 2011; Elster, 2000; Hashim et al., 2010; Kairo et al., 2001; Lewis, 2005). Duration of inundation is particularly important (van Loon et al., 2016). In some cases rehabilitation can be achieved simply by reconnecting or improving site hydrology, e.g. by installing culverts under a road, reconnecting former aquaculture ponds or reopening lagoons (Brown et al., 2014; Elster, 2000; Ferreira and Lacerda, 2016; Lewis, 2014; Twilley et al., 1999). In contrast, sites that have an elevation below that of a natural front mangrove fringe are likely to have permanently saturated soil with poor drainage, leading to anoxic and potentially acidic soil (Holguin et al., 2001; Kristensen and Alongi, 2006). These factors have a significant negative impact on the outcomes of projects attempting to afforest mudflats and seagrass beds (Asaeda et al., 2016; Samson and Rollon, 2008; Stevenson et al., 1999).

Many rehabilitation projects start planting first without fully understanding the original cause of mangrove loss or why there is no natural regeneration on site (Asaeda et al., 2016; Lewis, 2005, 2000; Walters et al., 2008). Both of these factors might be mitigated by reducing and removing mangrove stressors specific to a site, such as obstructed hydrology or unsustainable anthropogenic activities (e.g. harvesting of mangrove wood) (Lewis et al., 2016). Other reported reasons for failure include herbivore grazing and footfall damage, poor planting method, lack of aftercare (e.g. weeding) and monitoring (Kodikara et al., 2017), barnacle infestation and high wave energy (i.e. inappropriate site choice).

In this paper we describe a study of community-level planting projects to assess survival rates and to identify factors that determine success or failure at the project level.

2. Materials and Methods

2.1 Location of Study Sites

Although specific regional and local contexts are very important and highly variable, multiple villages within two countries were studied in an attempt to produce some general conclusions. Thailand and the Philippines share the same Indo-Malesia bio-geo-climatic zone within the Indo-West Pacific (Duke, 2006; Tomlinson, 2016). They have extensive mangrove areas, on which a substantial proportion of the coastal inhabitants depend for their livelihoods and food (Balmford et al., 2002). Since 1945, both countries have experienced significant mangrove conversion to aquaculture and degradation for charcoal and fuelwood production, among other causes (Richards and Friess, 2016).

Table 1 lists the Thai and the Philippine villages studied in this large-scale investigation. This study combined ecological and social research to examine mangrove rehabilitation in the context of biophysical, silvicultural and social factors. Villages were chosen because they were located either within or near to an extensive riverine mangrove delta or had a significant area of mangroves nearby. In all cases mangroves were considered an important village resource and were used in some ways by a substantial part of the village population. Finally, village members had attempted mangrove rehabilitation or afforestation in the past. The exception to these selection criteria was village P3A in the Philippines (Table 1) which was included as it had conducted a record-setting ‘1 million propagules in an hour’ planting project (Escandor, 2012). Except for this final record-setting planting, all Philippine planting discussed here was funded by the National Greening Program (Department of Environment and Natural Resources, 2016), a large-scale bio-shield establishment scheme initiated after typhoon Yolanda / Haiyan in 2013. Some rehabilitation or afforestation sites had been attempted more than once and each attempt was assessed. A site was defined as an individual plot or area villagers had attempted to rehabilitate or afforest as a discrete project. In total 119 attempts at rehabilitating 74 sites were assessed.

Table 1 Site information on mangrove rehabilitation projects evaluated in Thailand and Philippines

Thailand

Village Number	1	2	3	4	5	6
Village Code	T1A	T1B	T2A	T2B	T3A	T3B
Approx. Lat Long	6.89° N 99.79° E	6.89° N 99.79° E	7.89° N, 99.16° E	7.89° N, 99.16° E	8.44° N, 99.96° E	8.44° N, 99.96° E
Province	Satun	Satun	Krabi	Krabi	Nakorn Sri Thammarat	Nakorn Sri Thammarat
Number of Rehabilitation Sites Assessed	13	11	9	6	5	3
Village Mangrove Area (Ha)[1]	407	592	319	176	3,894	257
Approximate Research Dates	Sept – Nov 2013	Dec 2013 – Feb 2014	Feb – May 2014	June – Aug 2014	Oct 2014 – Feb 2015	Feb – May 2015

Philippines

Village Number	1	2	3	4	5	6	7
Village Code	P1A	P1B	P2A	P2B	P2C	P2D	P3A
Approx. Lat Long	10.81° N, 119.5° E	10.81° N, 119.5° E	14.06° N 123.3° E	14.3° N 123.3° E	13.9° N, 123.2° E	14.0° N, 123.2° W	13.8° N, 122.8° E
Province	Northern Palawan	Northern Palawan	San Miguel Bay, Luzon	San Miguel Bay, Luzon	San Miguel Bay, Luzon	San Miguel Bay, Luzon	Camarines Sur, Luzon
Number of Rehabilitation Sites Assessed	10	8	3	3	1	1	1
Village Mangrove Area (Ha)[1]	126	856	Unknown	Unknown	Unknown	Unknown	NA
Approximate Research Dates	Sept – Dec 2015	Jan – Apr 2016	May 2016	May 2016	May 2016	May 2016	May 2016

1. Source: Local Dept. for Marine and Coastal Resources field offices (Thailand) and Dept. of Environment and Natural Resources field office (Philippines).

Many mangrove rehabilitation projects were attempted by Thailand's Department for Marine and Coastal Resources (DMCR) and the Philippine Department of Environment and Natural Resources (DENR) in the 1980s and 1990s. However, this study looked only at more recent planting from approximately 2007 onwards, which involved participation by local villages. Assessment of village P1A's (Philippines) rehabilitation ability was expanded because this village was commissioned by the government to plant not only within its own territory, but also in neighbouring villages.

All accessible P1A-rehabilitated sites were assessed because the planting team and the techniques used were the same. Some rehabilitation was carried out in both Thailand and the Philippines while the lead author was present in the village, (T1B Jan 2014, T3A Dec 2014, Oct 2015) providing an opportunity to act as an observer and witness techniques.

2.2 Assessment Method

2.2.1 Initial Visits with Village Mangrove Expert

During initial scoping interviews with villagers and village leaders, opinions were sought to ascertain which resident was most knowledgeable about their mangroves. In all villages consensus about a mangrove expert readily emerged, thus negating the need to perform a village expert ranking exercise (Davis and Wagner, 2003; Chalmers and Fabricius, 2007). All rehabilitation sites were then visited initially with the village mangrove expert to record site history, reasons for the previous degradation, history of the rehabilitation effort(s), planting dates, details of site preparation, silvicultural practice and species choice. Site details recorded included presence / absence of trees, presence / absence of natural regeneration (indicating whether a site might naturally regenerate on its own) and hydrological connectivity. Also recorded were site elevation (section 2.2.3), soil type (sand, silt or clay), presence of standing water and post-hoc interventions such as the use of fencing. In addition other factors likely to affect rehabilitation and plant establishment were noted, such as evidence or presence of grazing livestock or trampling damage. Soil salinity was measured either from available soil pore water or groundwater sourced from minor excavations up to 15cm deep (Bellingham and Stanley handheld refractometer). However, it should be noted that it was not always possible to measure salinity in some of the high mangrove zone assessments because of a lack of available soil water. This might have skewed the resulting analysis. The direction of this potential skew is uncertain. The locations of the boundaries of all the rehabilitation sites were recorded via a handheld GPS (Garmin 62stc). Subsequently these GPS waypoints were employed to calculate the area of each site using Google Earth Pro. All site features were photographed.

Because several sites were planted more than once, a distinction has been made between 'attempt' (n = 119) and 'site' (n = 74). Wherever possible, all previous attempts on the same site were evaluated (38% of assessments) as well as the final (or only) attempt on a site (62%). Seventy-five of the attempts were in Thailand, 44 in the Philippines. The majority of the rehabilitation sites were <0.3 ha, ranging from 0.001 – 50 ha (SD ±7.73 ha). The cumulative total area assessed was 164 ha.

2.2.2 Mangrove Establishment: Counts, Extrapolations and Area Calculations

Although there are a range of factors that could be measured when assessing rehabilitation (see Dale et al., 2014 for a review), propagule or seedling survival is an unequivocal measure of whether the plants had managed to establish and survive or not. Presence or absence of natural regeneration was noted at the time of assessment - distinguishable from planted material by not being in lines, unevenly spaced, without canes and often of a pioneer species - but which did not contribute to survival scores. Plant health and vigour was also noted at the time of assessment.

Three techniques were used to assess survival depending on different planting ages and types of sites.

Preferentially, we used a 'full count' method for more recent planting events as both Thai and Philippine villages usually used canes which indicated where planting material had been inserted. Planting was frequently conducted in straight lines and even spacing. Therefore, for more recent planting projects (i.e. less than 1-2 years old) in less exposed sites, missing or absent plants were immediately obvious due to the resulting gap left in the lines of plants. Where possible every plant was counted for each generation of planting (if applicable). However, ten large-scale planting attempts were too extensive to allow each surviving plant to be counted. These extensive sites were stratified by elevation, exposure and channel edge / interior. Sub-plots were assessed to incorporate all significant variation of a site in order to achieve a minimum sample of at least 10% of the surviving plants.

Where full count inventory was not possible, we extrapolated counts from surviving patches of planting to the whole site. Some rehabilitation sites were too small or too fragmented to justify planting in lines. If present, surviving patches indicated how densely the site had been planted originally. In combination with a site history and the opinion of the village expert, total numbers planted were estimated and contrasted with survivors present, to produce a survivorship percentage for each generation of planting (if applicable).

In some cases, particularly on mudflat sites, there was often little trace of planting activity, or insufficient survivors to assess survivorship either via the ‘full count’ method or by extrapolation of surviving patches. Therefore we asked the village expert and participants of the planting to indicate as accurately as possible the boundary of the planted area, which was then marked by GPS. We then counted every surviving plant within this defined planting area. Subsequently Google Earth Pro was used to determine the area of the planting site. The stated planting spacing, normally 2x2m, was then used to calculate numbers originally planted. By dividing the number of surviving plants by the estimated number that had originally been planted, a survivorship percentage could be produced. For example, a planting area described by the village expert, marked by GPS, drawn as a polygon on Google Earth Pro might be revealed to cover 10 ha. If the stated planting density was 2x2 m spacing, this area would have originally had 25,000 plants. If the survivors counted within this defined planting area numbered 500, the survivorship was 2%.

These three different methods of survivorship assessment engendered different levels of confidence. To reconcile possible differences between methods, a post-hoc resampling was conducted using the extensive field photography to reassess all 74 sites. On the assumption that the 'full count' method produced the most accurate, bias-free estimate of survival, we recalibrated 'extrapolation from surviving patches' against the 'full count'. This post-hoc reassessment suggested that there was only a minor under-estimation of survival at low levels of survival, and a corresponding minor over-estimation of survival at higher levels of survival. Therefore, once reconciled, all three data sets were subsequently treated in the same manner. 'Full count' method was used for 38% assessments, 'extrapolation from surviving patches' 52% and 'counts within a defined area' 10% of attempts.

2.2.3 Mangrove Zones and the Quality of the Hydrological Connection

On any of the sites examined, several biotic and abiotic gradients were potentially affecting where mangroves lived, resulting in distinct bands of species. Most influential among these factors was the frequency and duration of a site's inundation due to its elevation relative to sea level (van Loon et al., 2016). Following Duke (2006) and Tomlinson (2016), bands of mangrove species were classified into three zones. The 'low' zone, which started at approximately mean sea level, received inundation at high tides >45 times a month and was characterised by species such as *Sonneratia alba and Avicennia alba*. 'Mid' zones were inundated by normal high tides 20 to 45 times a month and were the home of *Rhizophora* spp. and *Ceriops tagal*. 'High' or 'back' zones received inundation <20 times a month at high tide and included back mangrove species such as *Heritiera littoralis*, *Lumnitzera spp.*, *Scyphiphora hydrophylacea* and *Acrostichum* spp. Mudflats, which normally occurred between lowest water and mean sea level, were inundated by every high tide.

Table 2 illustrates the distribution of rehabilitation attempts within these mangrove zones. Most rehabilitation or afforestation attempts were on mid mangrove areas (52%), mudflats (30%), together with high zone areas (13%).

Table 2. Frequency of rehabilitation attempt by mangrove zone, by country

		Position of Rehabilitation Attempt Relative to Tidal Inundation Regime				
		Mudflat	Low Zone	Mid Zone	High Zone	Total
Country	Thailand	7	1	52	15	75
	Philippines	29	4	10	1	44
Total		36	5	62	16	119

Mid and high zone rehabilitation sites varied greatly in hydrological connection to tidal flushing, thus elevation per se was not necessarily a good indicator. Instead better hydrological connection was judged by the following indicators:

- greater number of days a month the site was inundated, according to the village expert
- many seeds / propagules present on the ground not directly under a potential seeding tree (indicating that inundations were able to transport them onto the site)
- greater presence of established mangrove natural regeneration (indicating that soil drainage was adequate for plant growth)
- wet soil and other evidence of the area having been recently inundated (e.g. visible tide line)

- a lack of extensive areas of standing water (indicating better drainage and suggesting a better quality of soil, as saturated soils are less well suited for mangrove establishment)
- a lack of visible salt crystals on the soil surface (indicating that sufficient inundation was avoiding a build-up of salt – a stressor for all mangroves)
- limited plant / tree stress indicators (e.g. canopy die-back, stunted plants, abnormally small leaves, a proliferation of prop roots on *Rhizophora* sp.)
- fewer dead leaves on the ground (indicating that they had been washed away)
- no significant debris within the channels, e.g. from cutting for charcoal production (debris would slow water flows, inhibit the distribution of seeds and propagules and increase the chance of sedimentation within the channels)

A qualitative decision was made by weighting all the above criteria equally. We classified each site's hydrological connectivity as either 'good' or 'partial / poor' based on the preponderance of indicators of good connection compared to indicators of poor connection. Mudflats and lower mangrove elevations by definition have good connectivity to the local hydrology and therefore were not assessed for the quality of their hydrological connection.

2.2.4 Time Since Planting

One hundred and nineteen attempts at mangrove rehabilitation or afforestation were evaluated over 74 sites. Of these attempts 36 were assessed less than 12 months after planting. We attempted to achieve a balance between including the maximum amount of data possible yet avoiding false-positives by excluding planting that had not yet had sufficient time to either establish or fail to establish. The cut-off was set at one year. The exception to this cut-off period was planting attempts where survivorship was ≤5% (14 planting attempts) as the planting within these attempts had already clearly failed. Therefore 97 attempts were retained for analysis.

Table 3. Time between planting and assessment, by frequency of rehabilitation attempt

Time between Planting Attempt and Assessment	All Attempts Assessed	Planting Attempts Retained for Further Analysis
< 1 Year	36	14
13 – 24 Months	29	29
> 2 Years	54	54
Total	119	97

2.2.5 Criteria for Judging Whether Planting was Required

An assessment was made as to whether each mangrove rehabilitation site might have regenerated naturally, whether rehabilitation should never have been attempted at that site, or whether planting was necessary and appropriate. Whether planting was necessary and appropriate or not was assessed by the following indicators:

- an absence of natural regeneration and / or a lack of successful establishment of natural regeneration
- appropriate site elevation for mangrove establishment relative to sea level, and resulting inundation regime, (i.e. within either low, mid or high mangrove zones, with duration and frequency of flooding, as described in section 2.2.3.). Mudflats, extending from approximately mean sea level down to lowest water, hydrological channels and areas of standing water were deemed inappropriate places for planting and ecologically unsuitable for mangrove establishment (Lewis, 2005)
- low expected wave energy (the assumption was that young plants that were subject to significant wave energy will be damaged or uprooted and washed

away.) Assessment included evidence of erosion, whether the site was directly open to the sea and the opinion of a local mangrove expert

- soil mechanically firm enough to anchor a propagule or seedling appropriately, not so soft as to allow the researcher to sink into the mud up to the knees
- minimal levels of significantly-sized debris on site (which might be lifted by the tide and damage vulnerable plants)
- no inhibiting social factors such as uncontrolled animal grazing, boat impact, damage from footfall or destruction from the use of damaging fishing gear which scrapes along the sediment surface uprooting natural regeneration

A qualitative decision was made by weighting all the above criteria equally, and classifying each site as either requiring planting, able to naturally regenerate on its own, or an inappropriate site that will never become mangrove, based on the preponderance of indicators described above.

3. Results

3.1 Site Descriptors and Demographics for All 119 Attempts

Hydrological connection, by definition, was complete for mudflats and low zone mangroves. However, for mid and high mangrove zones, some only had partial / poor connection and drainage (section 2.2.3) with a limited exchange of water at each tidal flushing, and areas of standing water. Of all the attempts within mid and high mangrove zones (n = 80) only a quarter (26%) had a good hydrological connection. There was no evidence that any measures had been taken to improve hydrological connection in those sites with partial / poor connection. Occasionally, hydrology was made worse (e.g. village T2A), by skimming the grass off a site with a bulldozer during site preparation, thereby filling the drainage channels in the process. On other sites, previous tree felling for charcoal had left brush and debris in the channels (e.g. village P1A), slowing the flow of water and increasing sedimentation in the channels.

High and mid zone mangrove soil salinities (both 27ppt, SD ±2 and SD ±8 respectively) were slightly less than low zone salinity (33ppt, SD ±2.3), which in turn was less than sea water (normally approximately 35ppt). Partial / poor hydrology appeared not to affect average mangrove soil salinity as much as the presence of fresh water input from rivers flowing into mangrove deltas.

A majority of rehabilitation attempts (65%) 'direct planted' propagules into the soil. Thirteen percent of attempts (all in the Philippines) used 'wildlings', young plants with 2-5 leaf pairs, pulled out of their original location and transplanted as bare-root stock. Eleven percent of rehabilitation attempts used polybagged seedlings. Rehabilitation was left to natural regeneration in only two instances, which have been included in the analysis because using this form of rehabilitation was a conscious decision on the part of the village (T2A) conservation group.

Fig. 1 illustrates in which zone the different types of planting material were used. This broad distribution suggests there was little relationship between planting material used and site elevation. Direct planting of propagules was the most common across all species except *Nypa fruticans*.

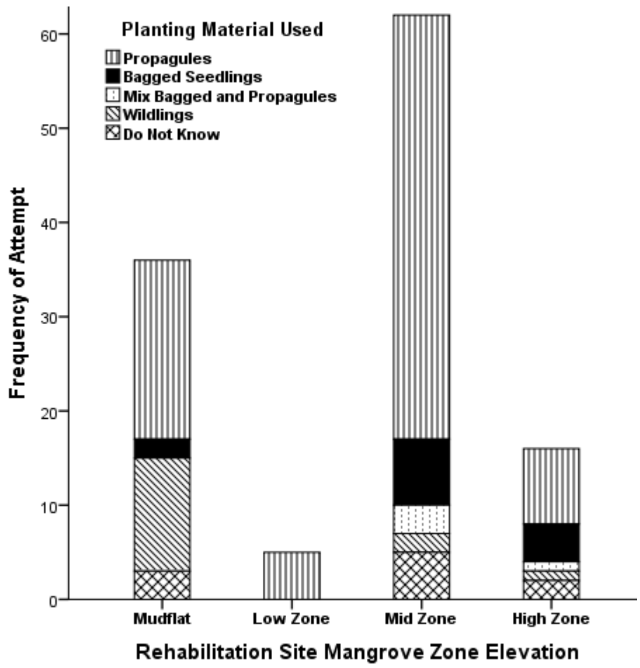

Fig. 1. Frequency of mangrove zone planted, by planting material used. (Natural regeneration has been excluded for clarity.)

By species, *Rhizophora* spp. was used in the majority of planting; alone in 52% of attempts and in conjunction with other mid mangrove species (e.g. *Ceriops tagal*, *Bruguiera* spp.) another 13% of the time.

Other mid mangrove species such as *Ceriops tagal* and *Bruguiera* spp. were planted 19% of the time (Fig. 2) . 'Mix' (n = 6) denotes when a selection of (rarely more than three) species was used from more than one mangrove zone. These often but not always included *Rhizophora* spp., along with *C. tagal, Bruguiera* spp. and very occasionally mangrove associate *Pandanus tectorius* (Kitamura et al., 1998; Tomlinson, 2016).

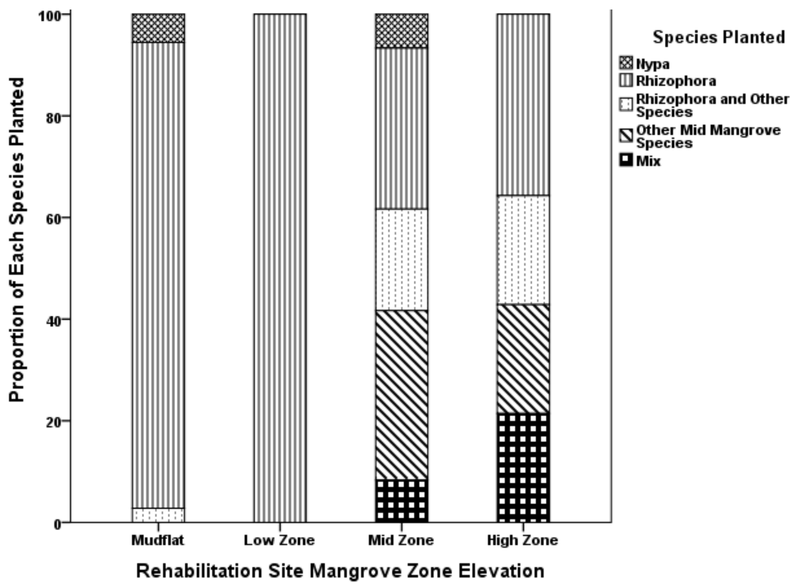

Fig. 2. Proportions of mangrove species used by mangrove zone.

3.2. Rehabilitation Successes and Failures

All analyses from this point onwards excludes the 22 attempts assessed as ‘too recent to judge’ (section 2.2.4) unless otherwise stated. For this reduced subset of rehabilitation attempts (n = 97), the mean survival rate was 20% (SD ±23.4) with a median of 10%, Fig. 3, the median or middle score being less affected by a non-normal or skewed distribution of data and extreme scores (Field, 2018).

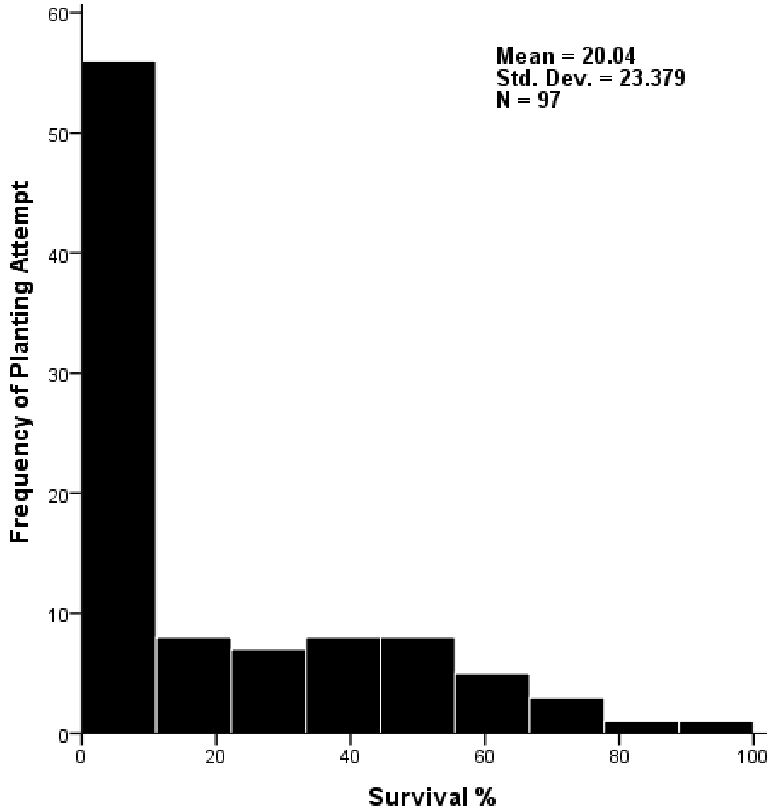

Fig. 3. Percentage survival rates by frequency.

The difference between 13-24 month and > 2-year planting survivorship was not significantly different ($p = 0.54$), indicating that most propagule death occurred within the first year after planting, Table 4.

Table 4. Mean survivorship by time between planting and assessment

Mean Survivorship by Time Between	< 1 Year	13-24 months	> 2 Years	Total

Planting and Assessment				
Mean Survival %	1.6	23.9	22.8	
SD	2	27.4	22	
N	14	29	54	97

Mean planting survival varied significantly (p < 0.001) between Thailand (26%, SD ±24.3, n = 58) and the Philippines (11%, SD ±18.8, n = 39). This reflected a tendency to attempt to afforest mudflats in the Philippines. The mean survival for mudflats was low (1.4%, SD ±3.6, n = 31) compared to mid mangrove zones (30.1%, SD ±22.5, n = 48) or high mangrove zones (25%, SD ±28.3, n = 13). Salinity exhibited a significant inverse relationship with planting survivorship (p < 0.001).

Fig. 4 shows the survival rates by mangrove species. The mean survival rate of R*hizophora* spp. was 11% (SD ±20.4, n = 50), despite being the most popular choice for planting. The establishment of *Nypa fruticans* was similarly poor (9%, SD ±10.4, n = 5). Other mid-mangrove species fared better with a mean survival of 29% (SD ±26.8, n = 20), as did ‘Mix’ (i.e. a range of species from more than one mangrove zone, 46.2%, SD ±22.8, n = 6).

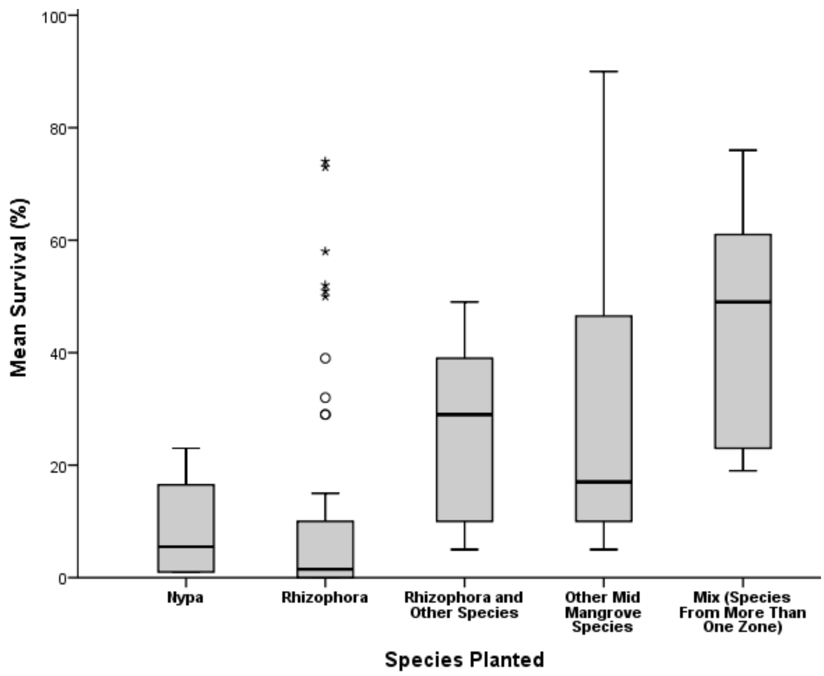

Fig. 4. Survival rates by species planted.

While there was no significant difference in survival between directly planted propagules and bagged plants, ($p = 0.32$), there was a significant difference between propagules and wildlings ($p = 0.024$), and between bagged plants and wildlings, ($p = 0.022$), Fig 5.

Bagged plants (mean survival 27.6%, SD ±26.6, n = 9) were either *Nypa fruticans, Ceriops tagal* or very occasionally mangrove associate *Pandanus tectorius*. Otherwise, planting was 'direct planting' of propagules into the substrate (mean survival 20.2%, SD ±23.9, n = 62). Transplanted 'wildlings' (bare root stock, always *Rhizophora* spp., mean survival 5.4%, SD ±8.6, n = 14) were only used in the Philippines.

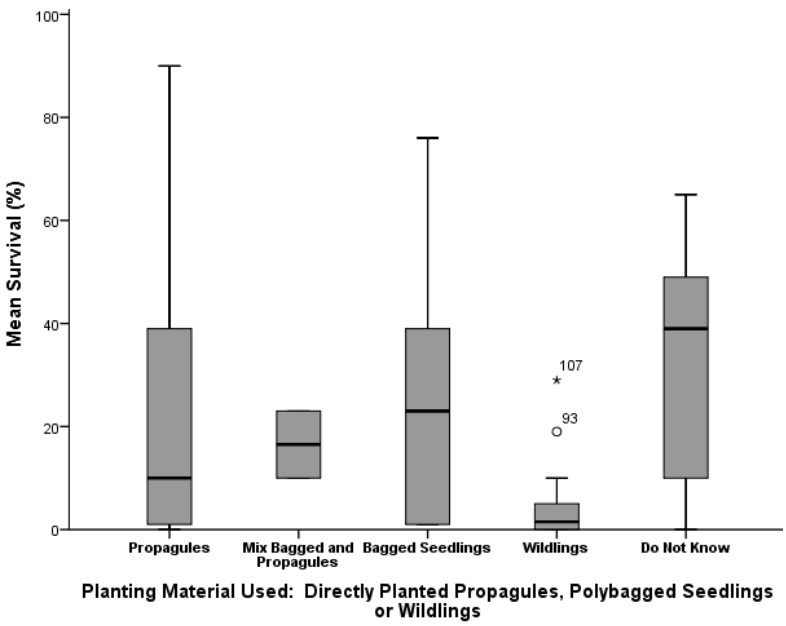

Fig. 5. Planting survival by type of planting material used.

Within the mid and high zone mangrove areas, mean survival of planted material was significantly lower ($p = 0.038$) in sites with partial / poor hydrological connection at 24.8% (SD ±21.9, n = 48), compared to areas with good hydrology where the survival rate was 39.9% (SD ±26, n = 15).

3.3 Interactions Between Factors

Table 2 shows that mudflats and mid mangrove elevations were frequently chosen as sites for afforestation / rehabilitation planting. Mudflats proved resistant to planting whatever form of planting material was employed. However, mid and high zone sites had better survival of all planted materials, and bagged plants (n = 9) in particular, Fig. 6.

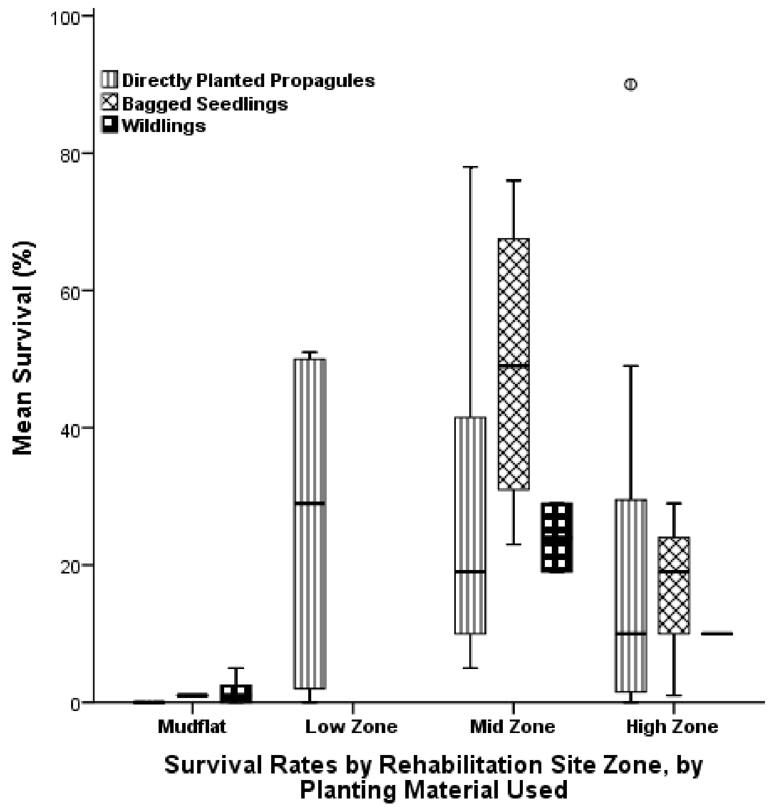

Fig. 6. Planting survival by mangrove zone, by planting material.
(Planting material category 'Don't Know' (n = 10) and 'Mixed' (n = 2) have been omitted for clarity.)

Fig. 2 (section 3.1) indicated the proportions of different species used for planting, at differing elevations. Fig. 7 illustrates that on mudflats and in back mangrove zones, *Rhizophora* sp. (n = 52) was not an appropriate genus to use. However, when

Rhizophora sp. was used in zones suitable for this genus (low and mid zones), its survival rate improved but was no more successful than ‘Other Mid-Mangrove Species’ (n = 21) which was only used in mid-to-back elevations. *Nypa fruticans* (n = 5) also performed poorly on mudflats.

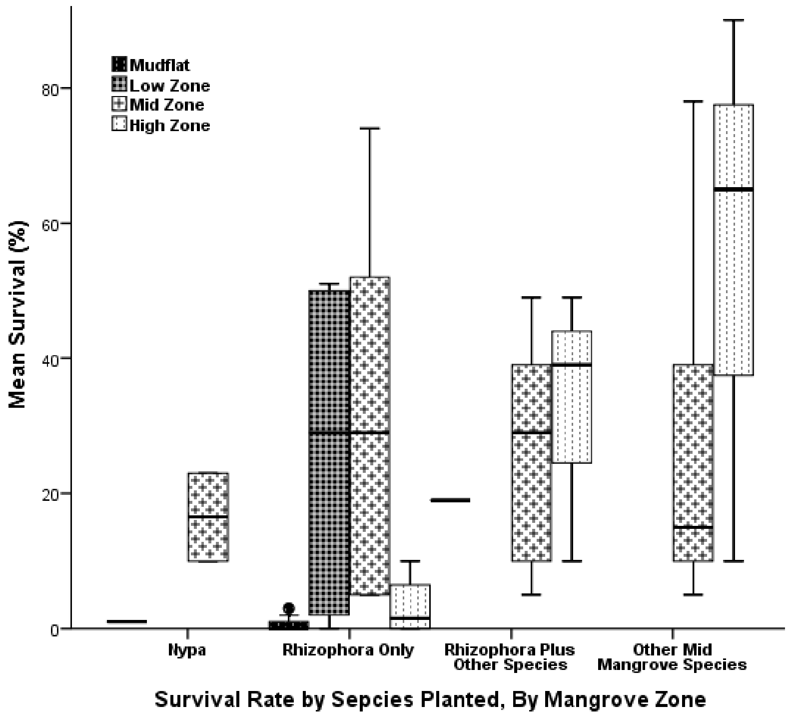

Fig. 7. Survival of species planted by mangrove zone.
(Mixed species (n = 6), natural regeneration (n = 2) have been omitted for clarity.)

3.4 Was Planting Necessary?

Planting survivorship was significantly higher ($p < 0.001$) when natural regeneration was present on a rehabilitation site (mean survival 26.3%, SD ±20.6, n = 51) compared to when there was no natural regeneration present (mean survival 13%, SD ±24.4, n = 46).

Using the criteria described previously (section 2.2.5) natural regeneration would have been sufficient, and planting unnecessary in 37% of attempts, largely within mid and back mangrove zones. Another 47% of attempts ‘will never be mangrove’ because of inappropriate hydrology or being located at an unsuitable inter-tidal elevation. For clarity of depiction, these two categories have been combined in Fig. 8 to contrast against the 16% of planting attempts that were considered to have been necessary, by mangrove zone.

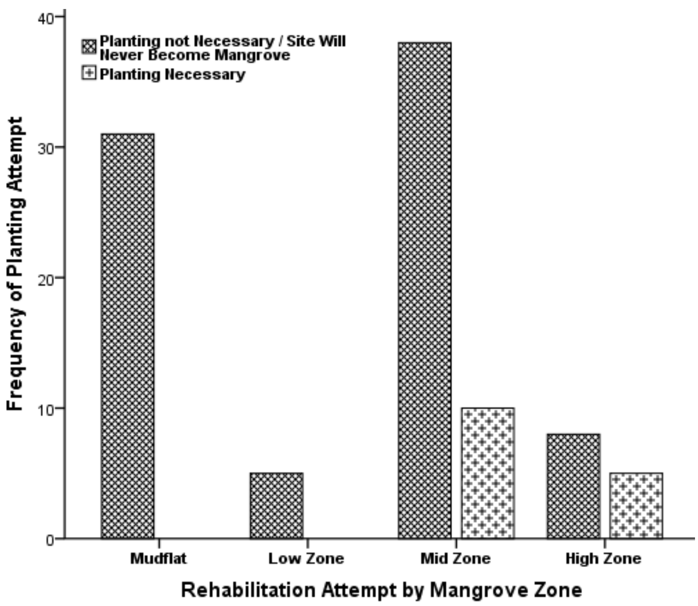

Fig. 8. Frequency of unnecessary/inappropriate planting against necessary planting, by mangrove zone.

4. Discussion

4.1 Research Method Limitations

More sites were assessed in Thailand than in the Philippines. Where possible, information from the village expert was cross-checked against interviews with government mangrove agency field office staff, villagers, and by direct observation, to reduce recall error.

Plant health, vigour and biomass characteristics were not included in survivorship assessment, but were taken into account for the quality of hydrological connection, the appropriateness of the site and species choice, and whether or not a site required planting. This inevitably involved an element of judgement and site interpretation, and consideration of factors such as the frequent seasonal floods in southern Thailand and watershed-scale hydrological disturbance in villages T3A and T3B (Osbeck et al., 2010; Prabnarong and Kaewrat, 2006), or the reduction of precipitation due to the 'El Nino Southern Oscillation' event that occurred during the research period (L'Heureux et al., 2017).

Separating and discarding 22 planting attempts which were 'too early to judge' (section 2.2.4) from those which had had 'enough time' to establish or fail, may have negatively affected survivorship results, but may also have removed potential real positives as well as false positives.

Although benchmarking against other mangroves (McDonald et al., 2016) might have been suitable in countries where there is pristine mangrove nearby, Thailand and the Philippines have very little mangrove which has not been replanted after charcoal / fuelwood concessions, subjected to species-selective felling or had natural *Sonneratia / Avicennia* forests replaced by *Rhizophora* spp. planting, such as in

Banacon Island, Philippines, or Pak Phanang Bay, Thailand (Macintosh et al., 2002; Osbeck et al., 2010; Walters, 2005). Mangrove workers who have suggested that rehabilitation projects should aim for and be judged by ecological rehabilitation criteria (Asaeda et al., 2016; Ellison, 2000; Lewis, 2000; Walters et al., 2008) are by implication working towards the conditions which allow the return of full ecosystem function (Saenger et al., 2013). Although appropriate in theory, using such criteria presents a practical problem as a result of the extensive time needed between planting and full recovery of ecosystem function. To have a chance of returning an area to functioning mangrove forest, the initial planting must first survive any transplant shock and establish itself. The data presented here only describe this initial establishment. We acknowledge that planting which might become established and grow into a new stand and might therefore be deemed successful, could still potentially fail to deliver the full suite of ecosystem benefits. Examples of this later failure include mangroves used to stabilise the walls of aquaculture ponds but which have little hydrological connection, or when mangroves are planted in drainage channels which block the local hydrological connection, leading to eventual ecosystem failure.

4.2 Discussion of the Results

The majority of sites that would probably have recovered through natural regeneration alone were mid and back mangrove, Fig. 8. Within these zones, some areas viewed by the villagers as ‘degraded’ were simply mangroves with natural gaps and desirable forest complexity. However, because they were seen as degraded they were re-planted, which sometimes included clearing biodiverse natural regeneration and ‘crown lifting’ of existing non-*Rhizophora* sp. trees (Walters, 2004). Only a few sites that had previously been mangrove before being cleared or degraded, normally for charcoal, were not regenerating (16%). Typically, this was due to poor hydrology, hard smooth soil making the retention of ‘volunteer’ propagules / seeds difficult or for other reasons such as a lack of fencing to keep out grazing animals (Field, 1996). In these cases planting was necessary and might ultimately facilitate quicker mangrove succession (Ferreira and Lacerda, 2016; Lewis et al., 2016), but with no guarantee of success because the other site-specific mangrove stressors, discussed here and in section 2.2.5, were often not resolved.

If planted sites would have regenerated on their own, without planting intervention as demonstrated by Lewis (2005) and Brown et al. (2014), this could avoid planting costs and liberate financial and labour resources for other management tasks. Generally, the presence of natural regeneration is a good indicator that a potential site in suitable for rehabilitation. However, natural regeneration can also start to establish in hydrological channels following the failure of the local hydrology. Similarly, although some of the mudflat afforestation attempts were situated near the fringe of existing mangrove, and hence were interspersed with a limited amount of pioneer species natural regeneration, this did not mean that these sites were potential mangrove areas. In short, open mudflats and mangrove drainage channels (47% of 97 attempts) were not ecologically appropriate sites, and rehabilitation / afforestation should not have been attempted in these locations.

The mangrove zone within the inter-tidal range runs from above mean sea level (Alongi, 2002; Kairo et al., 2001; Lewis, 2005) or upper third (Saenger, 2002) to highest high water. Knowledge of mangrove species zoning is essential for successful rehabilitation (Kairo et al., 2001). So-called site / species matching has been offered as a key reason for planting failure – i.e. planting inappropriate species for a given site and its inherent conditions (Alongi, 2002; Aung et al., 2011; Bosire et al., 2006; IUCN, 2017; Kodikara et al., 2017; Primavera and Esteban, 2008; Saenger, 2002; Walters et al., 2008). The failure to improve planting performance despite increased financial spend by NGO-led projects in the Philippines (Samson and Rollon, 2008; Walters, 2008) or the 1bn Peso (£14m) 'National Greening Programme' in the Philippines (Ranada, 2015) is in part due to the frequent planting of mid zone *Rhizophora* sp. in all zones (Fig. 2). This is possibly because its propagules are easy to collect and handle and do not require growing-on in a nursery (Lewis, 2014; Primavera, 2015; Primavera et al., 2011; Primavera and Esteban, 2008). The research described here demonstrates the improved success rates associated with planting the correct species for the specific mangrove zone (Fig.7).

While acknowledging the challenges of hydrological assessment (van Loon et al., 2016), an understanding of site hydrology, topography and drainage, and the effects these have on salinity and the species chosen, is vital for successful mangrove rehabilitation (Aung et al., 2011; Elliott et al., 2016; Elster, 2000; Hashim et al., 2010; Kairo et al., 2001; Lewis, 2005; Oh et al., 2017). Some sites can be restored simply by hydrological reconnection or improvement if propagules are available from nearby stands via hydrochory (Prach and del Moral, 2015; Stevenson et al., 1999). Unlike Elster's Colombian experience (2000) and Brown et al., (2014) in Indonesia, hydrology was rarely considered at our study sites, having been discussed only once at one Thai site (village T3A). Occasionally site hydrology was made worse by inappropriate site preparation. This study has documented the significant difference improved / adequate hydrology makes to rehabilitation success. This therefore suggests that many of the mid and back mangrove sites would have benefited from improved hydrological connectivity and drainage. However, guidelines for hydrologic rehabilitation are sparse and communication between researchers and mangrove managers appears to have been insufficient to change rehabilitation activities.

Although there was no significant difference in the survival rates of directly planted propagules and bagged seedlings (Fig. 5), extrapolation of these results should be done with caution. Bagged seedlings tended to be *Ceriops tagal* and *Nypa fruticans* not *Rhizophora* sp. and were likely to be used in a more appropriate zone (Fig. 6). However, planting of bagged *N. fruticans* on mudflats resulted in total mortality (village T3B). Bagged material was only deployed if it was provided by the government, rather than for ecological or silvicultural reasons and used much less often than direct planting of propagules (section 3.1). Excluding special cases, the resulting small sample sizes were too small to make further analysis appropriate.

Clump planting propagules close together (i.e. < 30cm apart) to allow planted material to benefit from a mutually improved rhizosphere (Chan and Baba, 2010; Lavieren et al., 2012) was never attempted. Root-balled ‘wildlings’ were not attempted by any group. Bare-root wildlings were only used in the Philippines, where villagers and government staff believed they were more reliable than propagules. Contrary to this local belief, bare-root wildlings were significantly less likely to establish than other planting material (Fig. 5). However, because these wildlings were most frequently deployed on mudflats, their very low survival (mean = 5.4%) also found by Primavera et al. (2011), cannot definitively be ascribed to bare-root wildings being an intrinsically poor silvicultural method. Furthermore, poor handling, for example allowing exposed roots to dry out in direct sunlight before being re-planted, cannot be ruled out. Poor survival of directly planted propagules might also have resulted from propagules being collected from trees before maturity, and planters having only a partial understanding of the effects of pests such as *Poecilips fallax* beetle on propagules.

Protection from storms and strong winds is often a key motivator for mangrove planting and afforestation, particularly in the Philippines where village planting was funded by the 'National Greening Programme' (Department of Environment and Natural Resources, 2016). In the medium-term, the rehabilitation projects described here will produce densely stocked, even-aged plantations with limited structural complexity. This lack of complexity should be a cause for concern as research has shown that older plantation stands of *Rhizophora* spp. are more vulnerable to strong winds than other species. Furthermore, they have a poor ability to recover from storm damage because they lack latent buds and cannot re-grow from the base when the stem is damaged (Bosire et al., 2008; Salmo III et al., 2014; Villamayor et al., 2016). In addition the smooth canopy of an even-aged class stand slows wind less than a mixed-aged stand of uneven height (Villamayor et al., 2016). Structural complexity is characterised by a number of forest attributes such as basal area, tree height, tree species, tree density, biomass, foliage arrangement, canopy cover and understory (McElhinny et al., 2005). This complexity develops over time but could be accelerated through planting a diversity of species at a variety of spatial densities.

In order to implement the 'National Greening Programme', the Department of Environment and Natural Resources of the Philippines passes down extensive planting area quotas to the department's field offices. To fulfil these quotas, mudflats are frequently selected as they offer the necessary spatial extent (Primavera, 2015). Although mudflats in both countries might have been considered silviculturally inappropriate, these areas typically have uncontested land tenure (for a description of the land tenure issues, see Primavera et al., 2015, 2011; Samson and Rollon, 2011). They are therefore easily available, as other researchers have reported (Lewis and Brown, 2014; Primavera, 2015; Primavera et al., 2011; Samson and Rollon, 2008; Walters et al., 2008). Thus despite evidence in the published scientific literature, rehabilitation manuals and national media (Primavera, 2015; Primavera et al., 2011; Ranada, 2015), planting continues on mudflats, and sometimes even seagrass beds, even though mean survival rates were shown here to be <2%. Mudflats are particularly valuable for feeding shorebirds, producing income for local gleaners and food security (Primavera et al., 2011). Therefore on the rare occasions that mudflat planting survived, normally due to rapid accretion or deposition of sediment (pers. obs.), the value of substituting one ecosystem for another has been questioned (Erftemeijer and Lewis, 1999; Lewis, 2005).

Similarly in Thailand much of the mangrove management activity was driven by national propagule planting targets delegated to the mangrove agency field offices. These targets originated from successive four-year National Economic and Social Development Plans (for example, Office of the National Economic and Social Development Board, 2011, 2001). Field offices also received additional directives such as planting 840,000 propagules to celebrate a national event (National News Bureau of Thailand, 2016). Furthermore there was often a general desire by villages to carry out communal planting activity on national holidays. However, some field offices are starting to negotiate the return of aquaculture ponds which had been illegally established within the mangroves and other encroached former mangrove areas. Consequently, more planting was carried out in mid and high mangrove zones (section 3.1). Although the overall success rate was higher, the question remains as to how much of the planting was actually necessary.

This paper and others (Dale et al., 2014; Lewis, 2005; Primavera and Esteban, 2008; Salmo III et al., 2007; Samson and Rollon, 2008;) have suggested that, despite being largely unnecessary, planting has tended to dominate mangrove management activity. This is typically endorsed at the national level. Area planting targets set by the Philippines' National Greening Programme have produced sub-optimal outcomes, and planting has also arguably received too much emphasis in Thailand. Although such target-driven planting provides quantifiable measures (Mansourian et al., 2017), this is unlikely to be aligned with silvicultural best practices. Propagule survivorship would be a more appropriate measure, perhaps combined with an emphasis on recovering abandoned aquaculture ponds. The area of abandoned ponds in Thailand and the Philippines is not known, but in Indonesia alone there is estimated to be around 250,000 ha (Gusmawati et al., 2017). Aquaculture ponds are frequently located in mid and high zone mangrove areas which this study and others have shown to be a more appropriate elevation for mangrove rehabilitation. Restoring hydrological connectivity to these abandoned ponds to rehabilitate them back to functioning mangrove ecosystems (Primavera et al., 2011; Villamayor et al., 2016) would arguably be a more appropriate management task, particularly over the coming decades as sea level rise requires mangroves to retreat landward and upward (Gilman et al., 2008; Primavera et al., 2011).

5. Conclusion

This research suggests that attention to a few key factors can enhance rehabilitation outcomes. First, mangrove workers should ensure that the appropriate species are planted in the mangrove zone for which they are best suited. Second, appropriate hydrological connectivity with good tidal flushing and drainage improves project outcomes. Third, it is suggested that much mangrove rehabilitation is either unnecessary or conducted on sites which are inappropriate. Fourth, attempted afforestation of mudflat sites usually fails and is not recommended. Finally, rehabilitation projects should focus on survivorship rather than meeting area or propagule number targets which typically produce sub-optimal outcomes.

6. Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

The authors would like to pass on their most heart-felt thanks to the Editors of ECSS and the three anonymous reviewers whose inputs greatly improved this article. Sincere thanks go to many people who assisted this research: Assoc. Prof. Boosya Bunnag and Dr Pavinee 'Jin' Patanachan of King Mongkut University for acting as Thai supervisors and helping with village selection; the National Research Council of Thailand; the directors and staff of the Royal Thai Government's Department Marine and Coastal Resources mangrove field offices for their generosity with their time and knowledge; Dr Antonio Dano and Dr Portia Lapitan from the Philippine Ecosystems Research and Development Bureau and John Pontillas of the Palawan Council for Sustainable Development and the members of the Malampaya Sound Protected Area Management Board for permission to conduct this research.

Thank you also to Khun Phonsawan 'Gift' Jinowat, Khun Kamondham 'Tuan' Truatmakkha and Khun Petchrung 'Aey' Sukpong in Thailand; Valiente Milan and Jevy Simion in Palawan and Agnes 'Ging' Faustino and Jerry Quitorio for their insightful interpretation; Khun Dear, Yosuke Fukushima san and Khun Namtan 'Namy' Kunja for helping with the transects; Jim Enright and Khun Jaruwan 'Ning' Kaewmahanin of NGO Mangrove Action Project for the use of the office, research advice and long-term support; Assoc. Prof. Dan Friess of the National University of Singapore for his GIS expertise; Dr Jean Yong of the Singapore University of Technology and Design for his mangrove species identification PDF; Prof. Rene Rollon of University of Philippines and Assit. Prof. Sev Salmo III of Ateneo University for their research advice. Finally thank you to the excellent people in the mangrove villages studied, for their generosity and willingness to share their lives.

7. Declaration of Interests

The lead author is a volunteer for NGO Mangrove Action Project (MAP) and periodically carries out paid ecological mangrove rehabilitation teaching on its behalf. MAP did not contribute in any way to the funding, design, analysis or writing of this paper. MAP has not run training for either DMCR or DENR. The second author declares no conflict of interest.

8. Authors' Contributions

Dominic Wodehouse carried out the fieldwork, analysis and the writing of the paper.

Mark Rayment developed the research questions, designed the research matrix, contributed several data capture techniques, added to the statistical analysis and edited the paper.

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