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Effectiveness of community-based mangrove management for biodiversity conservation: A case study from Central Java, Indonesia

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A R T I C L E I N F O

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A B S T R A C T

Efforts to rehabilitate degraded mangrove ecosystems in Indonesia started in the 1960s and have recently received increased attention. Rehabilitation efforts have been mainly conducted through community-based mangrove management (CBMM) programs, aimed at restoring important services such as food provisioning and coastal protection, and for biodiversity conservation. Our study assessed the effectiveness of CBMM strategies to conserve biodiversity in four adjacent Indonesian coastal villages (Sriwulan, Bedono, Timbulsloko, Surodadi) in Central Java. For this, we used complementary methodologies combining participatory resource mapping, semi-structured interviews, questionnaire-based interviews, field assessments and literature review. This yielded detailed information on mangrove rehabilitation activities, management approaches and the impacts of mangrove rehabilitation on biodiversity in the four villages. Our analysis focussed on mangrove forest structure and diversity and macro invertebrate diversity.

The overall comparison of management performance shows a higher achievement of CBMM applied in Bedono in terms of a larger mangrove diversity and net reforestation coverage, also supporting a higher macrobenthic faunal diversity compared to the other villages. The main contributing factors were a) the longer-term funding and maintenance, b) the greater acceptance for protective legislation, c) the higher levels of public support, d) the fact that more species of mangroves were used, e) the much larger spatial scale of mangrove restoration, and f) the presence of additional measures to reduce wave action in highly eroded areas. The results revealed key determinants of success when restoring mangroves for the purpose of biodiversity conservation and the influence of different CBMM approaches.

1. Introduction

More than 35% of the original mangrove cover was lost globally by the end of the 20th century (Valiela et al. 2001; Feller et al. 2017). Recently, the interest to rehabilitate these severely degraded ecosystems has increased (Macintosh et al. 2002; Andradi-Brown et al. 2013; Dale et al. 2014; Hamilton and Casey 2016). As host of the largest extent of mangroves worldwide, Indonesia exerts intensive efforts around projects that aim to protect (Alongi et al. 2016; Sidik et al. 2018) and rehabilitate degraded mangrove ecosystems. Efforts towards rehabilitation in the country started in the 1960s, mainly by the State Forest Cooperation (Perhutani) (Kusmana 2012; Kusmana 2014). High commitment to execute nationwide mangrove rehabilitation initiatives started in the early 90 s (Kusmana 2012; Kusmana 2014; Ilman et al. 2016). These initiatives were mostly conducted through community-based mangrove management (CBMM) programs that aimed at (re-) establishing mangrove forests either to optimize benefits for local communities (i.e. coastal protection, tourism, provision of foods, raw materials and medicines), or to balance these benefits with conservation (Setyawan and Winarno 2006; Amri 2008; Datta et al. 2012; Andradi-Brown et al. 2013; Brown et al. 2014). In 2020, the Government of Indonesia established a Peat and Mangrove Restoration Agency (BRGM) by Presidential Decree number 120/2020 and committed to rehabilitate 600,000 ha of degraded mangrove ecosystems in the country, among others to help absorb carbon emission (Peraturan President No.120 2020).

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Through CBMM, Indonesia was able to rehabilitate more than 130,000 ha (ca.30%) of its degraded mangrove areas by 2016 (MoF 2008, 2012; C. 2014; Hamilton and Casey 2016; MoEF 2017). Biodiversity plays a crucial role in improving ecosystem functions and the subsequent goods and services delivered by the rehabilitated ecosystems (Costanza et al. 2007; Benayas et al. 2009; Andradi-Brown et al. 2013). However, CBMM effectiveness, particularly with respect to restoring biodiversity, has been questioned (Brown et al. 2014). Therefore, our study aimed to investigate the effect of CBMM on mangrove biodiversity by comparing mangrove rehabilitation and management strategies applied in four neighbouring villages in Demak, Central Java, Indonesia.

Biodiversity refers to the variation among and within species and ecosystems (CBD 2003; Andradi-Brown et al. 2013). Mangrove biodiversity is commonly assessed using two indicators, namely forest structure and species richness (Field 1999). The forest's structural complexity and heterogeneity (i.e. vegetation structure and diversity) maintain ecosystem functions and facilitate colonization of diverse faunal communities (Hendy et al. 2014; Ferreira et al. 2015). In turn, mangrove structure and functioning are also influenced by faunal diversity, particularly macrobenthic species that depend on mangroves for all or part of their life cycle. Crustaceans and molluscs, for example, can modify the forest's physical and vegetation structure through burrowing and grazing activities. They can also form an important link between mangrove detritus and consumers at higher trophic levels, including birds and fish, and are therefore often used as bio-indicators of mangrove health (Macintosh et al. 2002; Ellison 2008). In this study, we

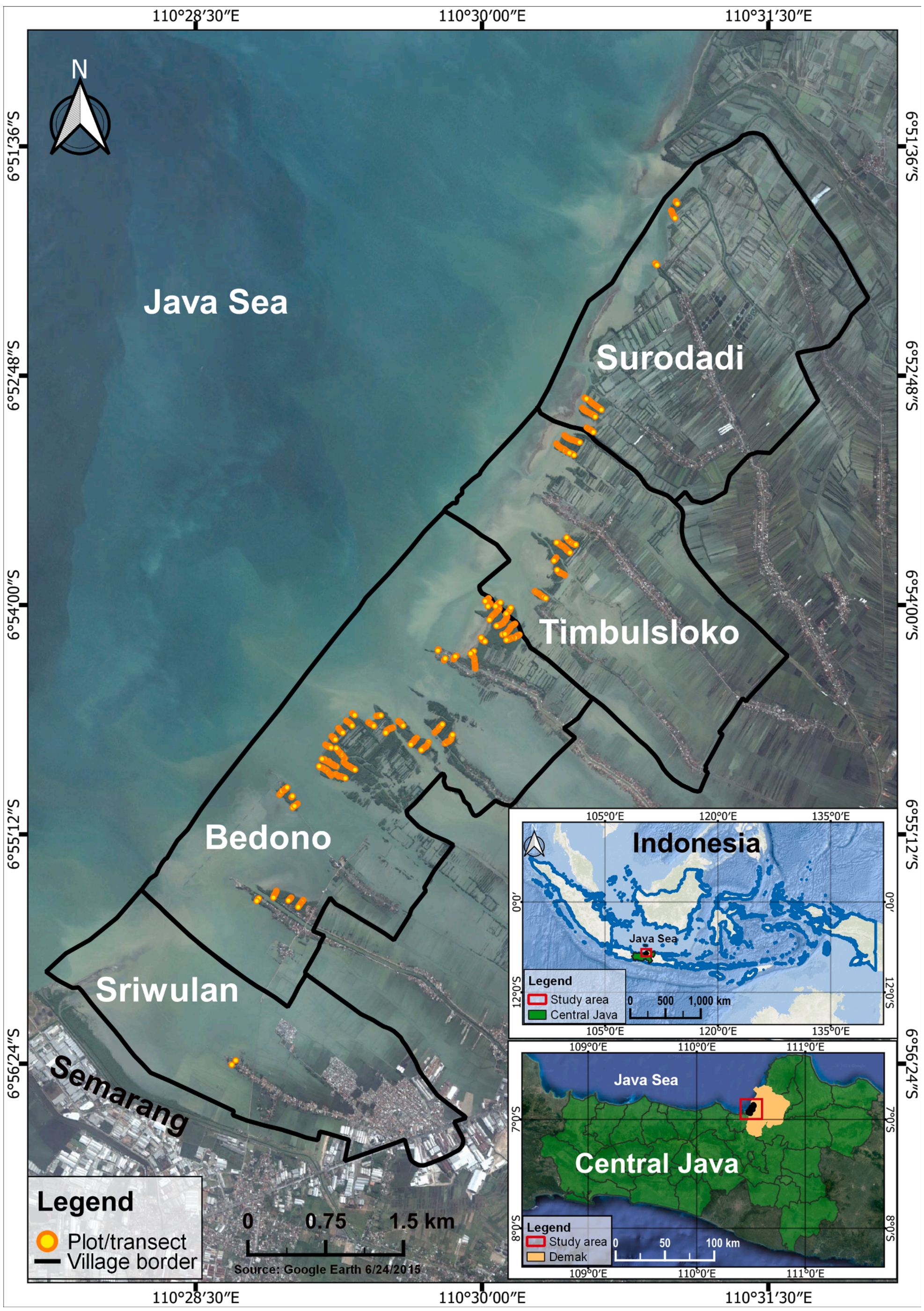

Fig. 1. Map of study area.

used mangrove structure and diversity as performance measures of the CBMM strategies applied in the four villages. For faunal diversity, we focused on macroinvertebrate fauna.

2. Study area

The study was conducted in four coastal villages (i.e., Sriwulan, Bedono, Timbulsloko, and Surodadi) located in Sayung Sub-district, Demak District, Central Java, Indonesia (Fig. 1). These four villages were selected based on the presence of CBMM practices, geographical similarity and the age of the rehabilitated areas which was around ten years or slightly older.

Originally, the four villages supported a larger human population than today, with livelihoods based mainly on rice cultivation and mangrove fisheries. The introduction of extensive aquaculture (in 1980s) destroyed the mangrove forest and the protection it rendered to the hinterland, gradually affecting the potential for rice cultivation. Aquaculture and fisheries have now also become marginal (Joseph et al. 2013). In addition, the study area was affected by soil subsidence at a rate of 2cm to 3cm per year, resulting in coastal erosion and the landward expansion of the tidally flooded area involving more frequent and deeper inundation (Chaussard et al. 2012; Taufani et al. 2018; Yuwono et al. 2018). As a result, the affected coastline retreated from the beginning of this century by 1km to 1.5km. Around 70,000 people were affected by coastal flooding and erosion hazards and entire villages have been swallowed by the sea. Many people experienced a major loss in income, reaching up to 60% to 80% in some villages (Wintertwerp et al. 2016). The four villages in our study similarly experienced the loss of productive land, homes and gardens, causing the forced emigration of more than 200 households (c. 1000 inhabitants in 2006), requiring major livelihood adaptation (Marfai 2012).

The mangrove rehabilitation efforts in these villages started in the 1990s and were implemented through a collaboration of local communities, local government, NGOs and other institutions including local universities (e.g., Diponegoro University). The rehabilitation activities successfully increased the mangrove forest in the study area from 7.5ha in 1996 to 240ha in 2015, accounting for nearly 25% of the total villages' areas (Damastuti and de Groot 2017). However, these rehabilitated areas are not connected in a continuous coastal green belt but are fragmented and scattered in separate areas along the coast, in aquaculture ponds, rivers and the settlements. Nearly all the mangroves in the four villages are tidally inundated on a daily basis, with average neap and spring tides of c. 0.1m and 1.1m, respectively. During the wet season, the wave height reaches 2m and tidal currents reach speeds of 0.5m per second (Muskananfola et al. 2020b). The sediments in Sriwulan, Bedono and Surodadi are dominated by silt and clay fractions (>70%) and the remaining is sand, whereas in Timbulsloko the sediments are dominated by silt (71%) and sand (21%) (Table 1). The salinity in the four villages ranges between 33ppt and 38ppt during the dry season and 27ppt and 31ppt during the wet season (Wisha and Ondara 2017).

Table 1
Salinity and sediments of the four studied villages.

Village	Salinity (ppt)	Sediment (%)		
		Sand	Silt	Clay
Sriwulan	34.5	0.6	85.3	14.0
Bedono	36.6	7.4	76.4	16.2
Timbulsloko	37.7	21.0	71.3	7.7
Surodadi	33.7	4.5	84.7	10.9

Note: Assessed during the dry season (August-October) in 2015.

3. Methods

3.1. Assessment criteria

We analysed the CBMM effectiveness for biodiversity conservation using 16 criteria classified by management characteristics (i.e., community governance, shared strategies and supporting local regulations) and management impact components (i.e., mangrove coverage, mangrove floral and faunal diversity) as shown in Table 2. These criteria were based on Datta et al. (2010); UNEP-WCMC (2011); Damastuti and de Groot (2017) and Morris et al. (2014).

3.2. Data collection

We combined different methods, including field assessment, participatory resource mapping , semi-structured interviews , questionnaire-based interviews and literature review to collect quantitative and qualitative information required for our assessment. The field data were collected within two periods, October 2014 to January 2015, and May to November 2015. The first period was used to collect preliminary data on mangrove rehabilitation and post-planting management strategies through participatory resource mapping and semi-structured interviews. The second period was used to gather information on biodiversity through forest and macrobenthic assessment and community perceptions of biodiversity. Secondary data were collected during both periods by reviewing government and local organization reports and documents, as well as academic publications and reports.

We applied participatory resource mapping in two villages (e.g. Bedono and Timbulsloko) to collect preliminary information on the actors involved in CBMM and the history of mangrove rehabilitation in these villages. The two villages were selected due to larger mangrove coverage on the seaside compared to Sriwulan and Surodadi. This mapping exercise involved 25 villagers representing different community constituents, i.e., gender, community organization and age-classes. The information was used to form a basis for semi-structured interviews . The semi-structured interviews involved 16 actors representing different institutions, including CBMM institutions, local government institutions and NGOs. During the semi-structured interviews, the respondents were asked about their background and their involvement in CBMM and details about mangrove rehabilitation and post-planting management strategies and their implementation. Furthermore, we used questinnaire-based interviews to gather information on community perception of the importance of biodiversity and village regulations for mangrove protection. We interviewed 500 household respondents,

Table 2
Mangrove management assessment criteria used.

Component	Criteria
Management characteristics	
Community governance	Organization of local collective action
	Local participation
	Communities' bargaining power in decision making
Shared strategies	Mangrove rehabilitation strategies
	Post-planting management strategies
Supporting local regulation	The attribute of the regulation
	Appropriation and prohibition
	Sanctions
Management impact	
Mangrove coverage	Rehabilitation scale
	Size of mangrove area
	Survival rate
Mangrove structure	Species
	Density
Mangrove floral and faunal diversity	Species richness
	Diversity index
	Species evenness

comprising nearly 10% of the total households in the coastal area of the four villages. The sample size was distributed equally with 125 household respondents per village. Starting from the first contact respondent recruited through participatory resource mapping, a snowball sampling (Biernacki and Waldorf 1981) was employed to find household respondents whose livelihoods depend on the mangrove areas or who are living in the proximity of mangroves.

Field assessments were employed to collect information on management impact on biodiversity. Field data collection took place from August 6 until October 6, 2015, using a transect line-plot method to assess forest structure, including species composition and community structure of the disconnected mangrove areas located adjacent to the coast (English et al. 1997). A total of 479 plots of 10m x 10m were assessed. Within each plot, two different sub-plots were made to assess the density of seedlings (1m x 1m) and saplings (5m x 5m) (English et al. 1997). The sampled plots represented 5% of the total mangrove area located on the seaside of the four villages (Appendix A).

Along the transect line of the vegetation analysis, we assessed the macrobenthic epifauna in 189 plots using quadrat sampling of 1m x 1m. All macrobenthic specimens found on the surface of the substrate within each sampled plot were counted and collected to be identified to the lowest possible taxon level (English et al. 1997; Yijie and Shixiao 2007). The macrobenthic infauna within the sediment was sampled using a corer, involving an iron pipe of 3.5cm diameter and 30cm length (Netto and Gallucci 2003; Ellis et al. 2006). The sediment was sifted using a 1 mm sieve and the benthos found through this process were preserved using 70% isopropyl and dyed with 0.2% Rose Bengal solution for identification in the laboratory (Netto et al. 1999; Netto and Gallucci 2003; Ellis et al. 2006; Bosire et al. 2008). Additionally, we measured the salinity and sampled the sediment in the macrobenthic plots for further analysis in the laboratory.

3.3. Data analysis

The information gathered through semi-structured interviews were transcribed, coded and organized into themes according to the assessment criteria as indicated previously. Community perception regarding mangrove biodiversity collected through questionnaire-based interviews was analysed using descriptive statistics in terms of relative frequencies. Data collected through field sampling were analysed for mangrove community structure using the method of English et al. (1997). The mangrove and macrobenthic biodiversity were described using species richness (S), Shannon's diversity (H) indices and Pielou's evenness (J). All mangrove biodiversity data was square-root transformed followed by a Wisconsin double standardization. The transformed and standardized data was then analysed by non-metric multidimensional scaling (NMDS) based on the measurement of Bray-Curtis similarity, in R software version 4.0.2 Vegan package 2.5–7 (Oksanen et al. 2020). We also analysed and visualised correlations between biotic and non-biotic variables using R software.

4. Results

4.1. Mangrove management characteristics

Most of the rehabilitation and management activities in the four villages were executed by involving local communities. Their involvement was generally organized through mangrove associations which were formed either on their own initiative (i.e., Karya Makmur in Surodadi) or by external (funding) institutions (e.g., government, NGOs, other institutions), with new projects sometimes initiating new associations. This resulted in a total of at least 14 mangrove associations in 2015 (Damastuti and de Groot, 2017), with multiple associations per village, except in Sriwulan. Some associations, such as Mangrove Bahari in Bedono, Rejeki Makmur in Timbulsloko and Karya Makmur in Surodadi, executed more extensive rehabilitation projects (Mangrove Bahari = 238ha, Rejeki Makmur = 150ha) compared to the others and thus functioned as the dominant reforestation actors in these villages.

The mangrove associations played an important role in determining and implementing the rehabilitation and post-planting management strategies applied in the four villages. However, many of these associations, especially those initiated by the government were highly dependent on external funding. Although the associations were encouraged to develop and propose rehabilitation projects, the final decisions regarding budgets and planting strategies often came from the funding organizations. This top-down decision-making process (Table 3) gave limited room for negotiation and feedback from local authorities. After the projects were implemented, the associations were gradually left to themselves without institutional assistance, reducing their ability to support local community-based initiatives.

On the other hand, the NGO-initiated association Mangrove Bahari in Bedono received long-term assistance and implemented various programs funded by the Organization for Industrial, Spiritual and Cultural Advancement (OISCA), involving mangrove planting, environmental education, construction, training and income diversification activities. Although the general decision regarding mangrove rehabilitation and management in this association was made in partnership with OISCA, the detailed arrangements in terms of project scale and budget were highly influenced by the NGO's budget and agenda. Table 3 provides further details on the key characteristics of community governance in the four villages.

Among all associations, Karya Makmur was the only self-mobilized collective action identified. This association stimulated self-empowerment among village members to sustain their livelihood by forming an occupational group. Rehabilitation and management activities were carried out independently, using funds collected from membership dues and providing the association with full authority in determining their rehabilitation and management strategies without external intervention. However, after leadership transition, this association eventually also became dependent on external funding, and decision making therefore ultimately took on similar forms as the government-initiated associations.

4.1.1. Rehabilitation and post-planting management strategies

The involvement of similar external (funding) institutions implementing national or regional mangrove rehabilitation projects in the four villages increased the tendency of strategy duplication in spite of differences in condition. Most of these projects, such as the National Movement of Forest and Land Rehabilitation and the Mangroves for the Future initiative have detailed technical guidelines which cover various procedures, among others, species, site and planting time selection, planting technique and post-planting management strategies. The main differences between the rehabilitation strategies applied by the four villages were in terms of scale and number of selected species (Table 4).

Based on our analysis, the rehabilitation scale in Bedono was the largest among all villages. The differences in rehabilitation scale were mainly influenced by the different number of projects and the scale of each project. Regarding the species used for rehabilitation, nearly all associations in the four villages chose mangroves of the Rhizophoraceae family. Despite its extensive presence in the four villages, only few associations, such as Karya Makmur in Surodadi and Mangrove Bahari in Bedono, sought to use the native species *Avicennia marina*, for planting. Nonetheless, this effort was stopped due to the higher complexity in nursery and planting processes that resulted in planting difficulties and higher seedling cost. Furthermore, *Sonneratia caseolaris* was used in Bedono to increase the useage value of the rehabilitated area. This effort was discontinued soon after initiation due to the high seedling cost. These findings show that species selection was strongly influenced by pragmatic considerations and budget constraints rather than local conditions or preferences.

With regard to post-planting management, none of the associations had a monitoring scheme that incorporated indicators for mangrove

Table 3
Key characteristics of community governance in the four villages studied.

Criteria	Sriwulan	Bedono	Timbulsloko	Surodadi
Organization of local collective action	Externally mobilized by district government and weak local leadership	Externally mobilized by NGO and district government	Externally mobilized by district government supported with strong local leadership	Self-mobilized by local actors
Local participation	Limited as labor	Obligatory based on membership with strong influence of dominant actors. Non-members are limited as labor	Limited as laborwith strong influence of dominant actors	Voluntary based on membership, strong influence of leadership and mutual-cooperation
Decision making	Top -down	Partnership limited by project	Top-down	Bottom-up

Table 4
Mangrove rehabilitation and post-planting management strategies in the four villages studied.

Criteria	Sriwulan	Bedono	Timbulsloko	Surodadi
Rehabilitation				
Scale/# plants	±350,000	±2,540,000	±1,350,000	±1,430,000
Species	*Rhizophora sp.*	*Rhizophora sp., Avicennia marina, Sonneratia caseolaris*	*Rhizophora sp.*	*Rhizophora sp., Avicennia marina*
Site selection	Based on funding	Based on funding	Based on funding	Based on necessity & funding. Mostly along the river and around the pond
Planting technique	Direct planting of propagules/ seedlings	Direct planting of propagules/ seedlings	Direct planting of propagules/ seedlings	Direct planting of propagules/ seedlings
Spacing distance	1m to 2m	1m to 2m	1m to 2m	1m to 2m
Protection measures	Bamboo stakes	Bamboo stakes	Bamboo stakes	Bamboo stakes
Post-planting management				
Monitoring	No scheme & records. Activities are voluntary or based on project by appointed officials	No scheme & records. Activities are voluntary or by appointed officials from NGO/ Government	No scheme & records. Activities are voluntary or based on project by appointed officials	Monitoring by appointed individuals. No recorded monitoring results
Maintenance	Based on project	Regular maintenance for OISCA's funded projects and project- based maintenance	Based on project	Maintenance by individuals for mangroves around the ponds, based on projects for mangroves on the seaside.

health, area and condition, nor set protocols for the monitoring. The monitoring concept as understood by the interviewees in our study refers to observation of the rehabilitation area to identify damage or activities that could pose a threat to the ecosystem and assess any changes. Karya Makmur in Surodadi, appointed one of its members to regularly oversee and report mangrove damage and destructive activities that could threaten the rehabilitated areas. Each member of Karya Makmur had an equal responsibility to monitor and maintain the mangroves planted around their ponds. For externally funded associations, monitoring was mainly conducted by an institutional field officer. Regarding the maintenance, only Mangrove Bahari in Bedono conducted regular maintenance, especially when executing the rehabilitation projects funded by OISCA. Every year from 2004 to 2007 the association regularly maintained the rehabilitated areas using a total of 34,000 seedlings funded by OISCA, to replace seedlings lost to mortality. Maintenance by other associations was largely dependent on whether the activity was included in the initial project proposal or if the community proposed the maintenance activities to external funding as a new-separate project.

4.1.2. Supporting local regulatory framework

All four villages instituted regulations aimed at managing and protecting the mangroves and coastal ecosystem from human disturbance. These regulations addressed the spatial boundaries for management and protected areas, management tasks, prohibited activities and specified sanctions that would apply to both villagers and non-villagers (Table 5). The rules related to biodiversity were expressed in measures such as the prohibition of mangrove logging, shooting or catching of birds in the mangrove areas and destructive fishing activities. Any violation of these regulations was subject to sanctions. Our results showed that these biodiversity-related measures were known and accepted by nearly 50% of respondents in Bedono, Timbulsloko and Surodadi. Whereas in Sriwulan less than 30% of respondents knew about these measures.

Despite legal protective measures and stipulated sanctions, bird hunting, destructive fishing (i.e. the use of destructive fishing gear and unsustainable mud crab fishing) and traces of mangrove logging were still encountered during our observations in Bedono. Unsustainable mud crab fishing was also found in the other three villages. This involved unselective catching of mud-crabs, ranging from juvenile to adult including the egg-bearing females, or use of extraction techniques that damaged mangrove roots. Of all villages, Sriwulan had the strictest rules against destructive mud crab fishing. However, due to a combination of poverty, lack of skills and knowledge of the importance of protecting juvenile crabs and egg-bearing females, lack of public awareness and insufficient efforts to communicate the regulations, destructive fishing practices continued in all villages (Damastuti and de Groot 2017).

4.2. Mangrove biodiversity

Most respondents associated mangrove biodiversity with the presence of different birds, fish and crustacean species, particularly those with high commercial value (i.e. mullet, mud crabs, milkfish, white shrimp, estuarine catfish and spotted scat). Based on our interviews, more than 80% of the respondents in the four villages acknowledged mangrove biodiversity as important, very important or strongly important for their livelihood. Bedono had the highest positive response (91%) compared to the other villages (on average 85%).

4.2.1. Mangrove coverage

Over 5 million seedlings were planted in the four villages through various rehabilitation programs implemented from 1999 to 2015. We estimated that the rehabilitation projects covered at least 567ha, based on the usual planting technique involving 1m spacing distance or equal to 10,000 seedlings per ha. The district government estimated a larger total mangrove area in the four villages, amounting to more than 1600ha (DKP Demak 2014). However, in 2015 the actual total mangrove area in these villages was much smaller than the estimated area of rehabilitation (Table 6). This difference indicates a high mortality, particularly in Sriwulan, where nearly 90% of the planted seedlings failed to grow.

Based on our interviews, the low survival rate in Sriwulan was

Table 5
Local regulatory frameworks in the four villages studied.

Criteria	Sriwulan	Bedono	Timbulsloko	Surodadi
Spatial boundaries defined	√	√	√	√
Management tasks	(7)	(7)	(7)	(7)
Protection of coastal area and the sea	√	√	√	√
Rule enforcement	√	√	√	√
Management planning	√	√	√	√
Daily execution and supervision	√	√	√	√
Monitoring	√	√	√	√
Fund raising and management	√	√	√	√
Coordination and collaboration	√	√	√	√
Prohibited activities	(8)	(6)	(5)	(6)
Mangrove cutting/ logging	√	√	√	√
Commercial use of mangrove	√	-	-	-
Herding cattle in mangrove area	√	√	√	√
Bird hunting	√	√	√	√
Destructive mud crab fishing	√	-	-	-
Destructive fishing	√	√	√	√
Operation of big scale fishers in the coastal area	√	-	-	-
Illegal commercial sand mining	-	√	-	√
Littering in mangrove area	√	√	-	√
Passing by, walking through and fishing in the non-fishing area	-	-	√	-
Sanctions	(6)	(7)	(6)	(6)
Warning or social sanction	√	√	√	√
Mangrove planting for cutting 1 tree (seedlings)	100	300	100	1000
Fine (IDR)	500,000	500,000 - 1000,000	25,000 - 100,000	-
Hunting weapon confiscation	-	√	√	√
Fishing gear confiscation	√	√	√	√
Reported to local authority or police	√	√	√	√
Legal process according to applicable law	√	√	-	√

Note: √ = present, - = not present

mainly influenced by an inappropriate timing of planting, high natural disturbance and the absence of additional measures to protect newly planted seedlings. The mortality rate usually increased during the peak of the dry season (August-September) due to desiccation and during the peak of the rainy season (December-February) due to storm activity and strong wave exposure. However, this local knowledge of such factors was often ignored or neglected due to the urge to meet the rehabilitation targets. Moreover, all four villages experienced severe coastal erosion. The level of erosion in each village varied corresponding to the distance from Semarang (Fig. 1). The highest erosion was observed in Sriwulan, whereas Surodadi, the most distant village from Semarang, experienced the least erosion. Nevertheless, the high intensity of coastal erosion in Sriwulan was not taken into account in the rehabilitation strategies. Likewise, additional measures, such as the construction of breakwaters to reduce wave energy in the rehabilitated areas (Jati and Pribadi 2017) and increase sedimentation (Matsui et al. 2012) were not incorporated. As a result, many rehabilitation efforts applied in this village failed. On the other hand, Bedono and Timbulsloko were also constantly threatened by massive erosion. However, in response, some government institutions and an international consortium led by Wetlands International built breakwaters in the coastal area of these villages through different projects (Wintertwerp et al. 2016). These additional measures likely helped in reducing the mangrove mortality rate and enhancing the rate of sedimentation which was expected to stimulate natural regeneration of mangrove vegetation (van der Lelij et al. 2021). The absence of such measures in Sriwulan was likely related to the high level of coastal erosion that caused reluctance of external institutions to implement coastal defense projects in this village, despite its urgency. Furthermore, the higher success rate in Surodadi appeared to have been influenced by two main factors namely lower coastal erosion rate compared to the other three villages and site selection which was mostly along the river and around the pond areas with better protection from wave exposure than along the coast.

4.2.2. Floristic diversity

We identified eight mangrove species, i.e., *Avicenia marina* (*Am*), *Avicennia alba* (*Aa*), *Rhizophora mucronata* (*Rm*), *Rhizophora apiculata* (*Ra*), *Rhizophora stylosa* (*Rs*), *Sonneratia caseolaris* (*Sc*), *Xylocarpus mol-luccensis* (*Xm*) *and Excoecaria agallocha* (*Ea*) present in the coastal zone of the four villages. These species were numerically dominated by saplings and seedlings of *Am* and *Rm* (See Table 7). The overall tree, sapling and seedling diversity in the four villages was relatively low, as the Shannon's diversity indices (H) value ranged between 0 and 1.4 (Fig. 2).

Sriwulan, the village that was most affected by erosion, showed a lack of natural regeneration with only *Rm* and *Ra* present in the coastal zone, all from planting. Some naturally recruited *Am* was seen scattered in the residential area and along the river outside of the sampling plots. The tree diversity in Sriwulan was the lowest among all four villages with only one species observed in the sampled plots (Fig. 2). The higher tree density (475 trees.ha^{-1}) in Sriwulan can be attributed to the planting method applied in this village, which sometimes involved narrow spacing distance (<1m) to avoid destruction and to compensate for the limited rehabilitation area. Bedono, the village that was the second hardest hit by erosion showed some significant natural regeneration (dominated by *Am*, but in previous years having a limited recruitment of

Table 6
The rehabilitation scale, mangrove size and survival rate of mangroves in the four villages studied.

Description	Unit	Sriwulan	Bedono	Timbulsloko	Surodadi
Total number of planted propagules/seeds[1]	#	±350,000	±2,540,000	±1,350,000	±1,430,000
Estimated mangrove area planted[2]	ha	±35	±254	±135	±143
Total actual mangrove area present[3]	ha	4	111	52	74
Seaside	ha	1	61	21	12
Ponds and settlement	ha	3	50	31	62
Survival rate[4]	%	11	44	38	52

[1] Rehabilitation projects from 1999 to 2014 funded by Marine and Fisheries Office, Agricultural Office, Environmental Office and OISCA (in Bedono).
[2] The estimated mangrove cover was based on the common planting technique applied in the four villages using 1 m spacing distance. Thus1ha = 10000seeds.
[3] Source: Sattelite imagery 2015 and semi-structured interviews.
[4] The Survival rate was estimated by comparing the total number of planted propagules/seedlings from 1999 to 2014 to total mangrove areas in 2015.

Table 7
Mangrove species and density in the transect sampled in the four villages studied.

Village	Species density (Ind ha^{-1})							
	Aa	Am	Ea	Ra	Rm	Rs	*Sc*	Xr
Sriwulan								
Tree	–	–	–	–	475	–	–	–
Sapling	–	–	–	2,300	2,400	–	–	–
Seedling	–	–	–	–	145,000	–	–	–
Bedono								
Tree	4	354	–	–	2	–	–	–
Sapling	30	3,843	–	10	1,032	52	1	–
Seedling	–	32,427	–	–	6,149	–	–	–
Timbulsloko								
Tree	31	39	–	–	7	2	–	–
Sapling	1,077	2,623	–	12	500	246	–	–
Seedling	8,750	13,558	–	–	14,231	5,096	–	–
Surodadi								
Tree	61	89	–	–	16	–	–	–
Sapling	1,026	1,626	90	39	961	239	–	90
Seedling	–	10,968	–	161	22,097	5,968	–	645

Aa and *Rs*), and some replanting (*Rm, Ra, Sc, Am*). Although Bedono had more sapling species (6) compared to Sriwulan and Timbulko, the diversity index was low since these species were not evenly distributed. Timbulsloko had been less affected by erosion than the south-western villages and had a limited natural stand of mainly *Avicennia* (*Am* and *Aa*) remaining. There appeared to be successful natural regeneration, dominated by saplings and seedlings of both *Am* and *Aa*. Near to the river, *Avicennia officinalis* was observed outside of the sampling plots. Surodadi, being located most northerly and distant from Semarang, was least impacted by erosion, and showed the highest biodiversity (H=1.43), with a significant number of sapling (7) species, dominated by *Am* and *Aa*, and a limited number of *Rm*. In this village, the success rate of replanting (*Rhizophora* spp.), with seedlings turning into saplings, appeared to be highest. Several surviving clusters of the mangrove palm *Nypa fruticans* were observed in March 2017, in water of a salinity of 10ppt (Debrot, pers. obs.)

4.2.3. Macrobenthic diversity

The rehabilitated mangroves in the four villages provided habitat for a wide range of resident and transient species, including numerous species of macrobenthos. A total of 31 species of benthic macroinvertebrate fauna were identified in all four villages, as follows: 20 molluscs (18 gastropods and 2 bivalves), 3 polychaetes, 1 Rhabditophora and 7 crustaceans (particularly Malacostracans) (Table 8). The epibenthic macroinvertebrate communities documented in the four villages were all dominated by gastropods. The density of these benthic species ranged from 0 ind.m^{-2} to 461 ind.m^{-2} (Bedono), 22 ind.m^{-2}to 346 ind.m^{-2} (Timbulsloko) 40 ind.m^{-2} to 225 ind.m^{-2} (Surodadi), and 7 ind. m^{-2} to 34 ind.m^{-2} (Sriwulan). Of all villages, Bedono had the highest total species richness (31 species), whereas the lowest was recorded in Sriwulan (9 species) (Fig. 3). The Shannon's diversity index was also higher in Bedono (H=1.8) followed by Surodadi (H=1.7) Timbulsloko (H=1.6) and Sriwulan (H=1.5). The macrobenthic species in Sriwulan (J = 0.7) were however more equally distributed than the other three villages.

4.2.4. Correlation between mangrove biodiversity and abiotic variables

The MDS ordination (Fig. 4) showed that most of the observed plots have relatively similar sediment characteristics (dominated by silt and clay fractions) and salinity levels (between 33ppt to 38ppt). Only a small number of plots in Bedono and Timbulsloko were different from the rest of the plots (Fig. 4a and Fig. 1), with the sediment composition being co-dominated by silt and sand fractions. Furthermore, the species richness, abundance and diversity of both vegetation and macrobenthic fauna on each of the measured plots in Bedono and Timbulsloko showed minor differences (Fig. 4b). In Sriwulan, two plots were relatively similar while the other two were distinct. Unlike the other villages, Surodadi seemed to have more variance in species richness, abundance and diversity.

Our analysis showed both positive and negative correlations between macrobenthos and vegetation in terms of richness, abundance and diversity in the sampled area of the four villages (Fig. 5 and Appendix B for a detailed correlation matrix). Tree abundance, for example, had a positive correlation with macrobenthic diversity (r = 0.190, P<0.01), but was negatively correlated with macrobenthic abundance (r=-0.199, P<0.01). Dense root structures in increasing plant density, as highlighted by Leung (2015), may be habitable for a more diverse macrobenthic community, but limit the living and foraging area, and thus may have accounted for the reduced macrobenthic abundance. Furthermore, macrobenthic diversity was negatively correlated to seedling richness (r=-0.174, P<0.05) and diversity (r=-0.191, P<0.01). The negative correlation is assumed to be the result of predation by some crustacean and gastropod species (e.g., *Episesarma versicolor, Metapograpsus latifrons, Melampus sp, Terebralia* sp.) that feed on seedlings and/or propagules (Fratini et al. 2001; Ashton 2002; Nagelkerken et al. 2008; Pribadi et al. 2014). This predation is assumed to have contributed to seedling mortality in the four villages. Propagule predation has been acknowledged as playing a significant role in seedling distribution in mangrove stands, and thus could potentially affect the survival of replanted mangroves (Sousa and Mitchell 1999; Ashton 2002; Clarke and Kerrigan 2002; Hidayat 2011)

Regarding the abiotic variables, our analysis showed negative correlations between salinity and seedling richness (r=-0.186, P<0.01) and abundance (r=-0.241, P<0.01). This result suggests that seedling survival increased as the salinity decreased. Salt requirement or tolerance increases as seedlings turn into saplings, which was shown by the positive correlation between salinity and sapling abundance (r = 0.259, P<0.01). Lower salinity, however, allowed greater tree richness (r=-0.240, P<0.01), abundance (r=-0.285, P<0.01) and diversity (r=-0.144, P<0.05), whereas to the contrary some benthic species were positively correlated with salinity (r = 0.340, P<0.01). Furthermore, the dominant silt fraction (Table 1) was positively correlated to sapling richness (r = 0.206, P<0.01) and diversity (r = 0.186, P<0.05) and macrobenthic abundance (r = 0.151, P<0.05), but negatively correlated to tree abundance (r=-0.259, P<0.01), seedling richness (r=-0.147, P<0.01) and benthic diversity (r=-0.193, P<0.01). The sand fraction, on the other hand, correlated positively to tree abundance (r = 0.257, P<0.01), seedling richness (r = 0.161, P<0.05) and abundance (r = 0.151, P<0.05), and benthic diversity (r = 0.184, P<0.01). The more limited range of variability in bottom clay composition correspondingly showed less influence on both benthic and vegetation richness and diversity compared to sand and silt.

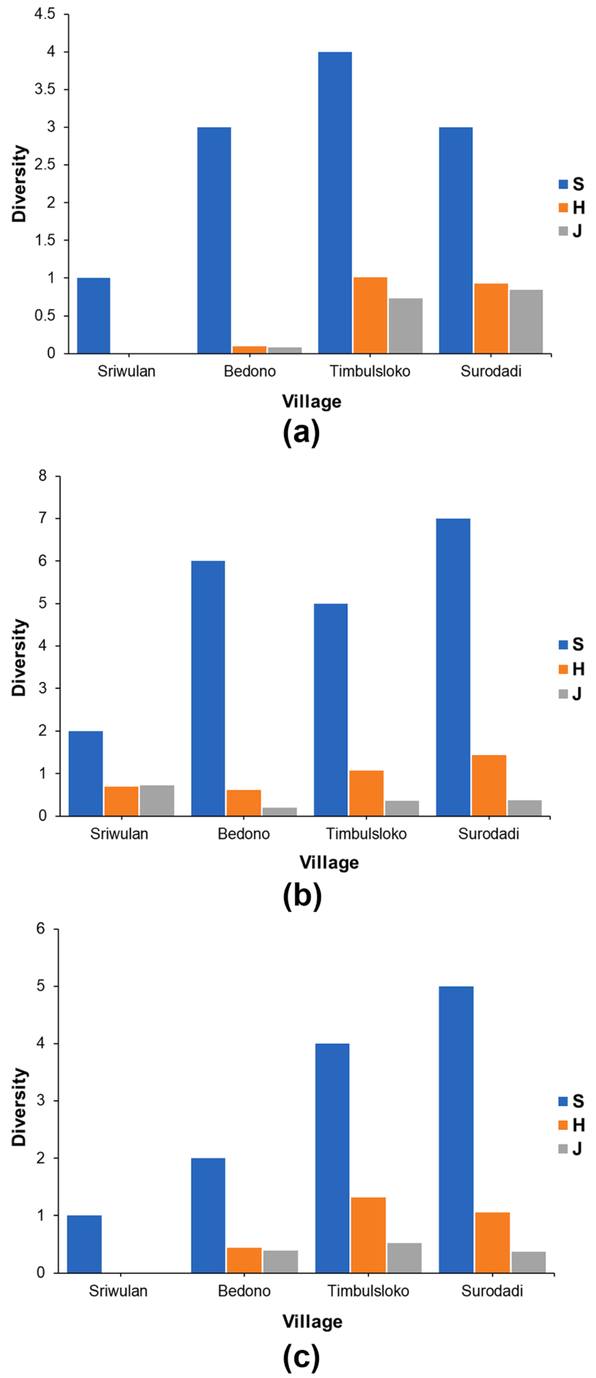

Fig. 2. Performance of the four villages on mangrove tree (a), sapling (b) and seedling (c) diversity indices.
S: Species richness, H: Shannon diversity, J: Pielou's evenness.

5. Discussion

Mangrove rehabilitation programs are increasingly being undertaken to re-establish ecosystem services in the context of community-based biodiversity conservation (Andradi-Brown et al. 2013). However, assessing the effectiveness of rehabilitation and management for biodiversity is challenging due to the wide array of different objectives and techniques. Hence, comparing different rehabilitation and management strategies and the resulting mangrove biodiversity can help to answer critical questions about how diversity develops and how it should be maintained (Purvis and Hector 2000). Nevertheless, there are uncertainties in the results as well as limitations to the applied methodologies which are discussed in this section.

5.1. Species selected for the biodiversity assessment

Mangroves support a substantial faunal diversity: micro and macroscopic, terrestrial and aquatic, migratory and resident (Macintosh et al. 2002). Selecting the type of species for mangrove biodiversity assessment is challenging because what is desirable needs to be compromised with what is possible (Buckland et al. 2005) in terms of methodologies, time and resources. In this study, we prioritized our empirical assessmentto the mangroves' dominant residents, particularly macroinvertebrate fauna. This species group was selected due to its important role in the bioengineering of mangrove systems and is often used as bio-indicator for mangrove health and the progress of mangrove rehabilitation and management (Macintosh et al. 2002; Ellison 2008; Nagelkerken et al. 2008). Furthermore, some species from this group serve as important sources of food for other fauna that resides permanently or temporarily in the mangrove areas such as fish and birds (Macintosh et al. 2002; Ghasemi et al. 2011). Thus, we assume that higher abundance of macroinvertebrate fauna will translate to a higher number of other mangrove associated fauna that feed on them and hence can serve as a useful overall index of system diversity.

We identified 26 macrobenthic genera belonging to five classes i.e., Bivalvia, Gastropoda, Malacostraca, Polychaeta and Rhabditophora. Our analysis demonstrated the expected correlation between both vegetation and benthic richness, abundance and diversity. The recorded benthic fauna was, however, different from similar studies recently conducted in the study area. Muskananfola et al. (2020a), for example, recorded a total of only ten macrobenthic genera belonging to three classes (i.e., Bivalvia, Gastropoda and Polychaeta), whereas Iqbal et al. (2021) documented 21 genera in four classes (i.e., Bivalvia, Gastropoda, Malacostraca and Polychaeta). Their sampling plots or stations were from Bedono and Sriwulan only, whereas our study covered all four villages. Results may be influenced by the use of different methodologies and the timing of assessments. Macrobenthic abundance and diversity can show great variation between wet and dry seasons (Muskananfola et al. 2020a, (Iqbal et al. 2021). Muskananfola et al. (2020a) collected samples using a 10 cm diameter pipe sampler during the wet season (March) and a 0.01m^2 van Veen grab sampler during the dry season (October). Likewise, (Iqbal et al. 2021) also covered two seasons (February and July), but only using an Ekman grab sampler. Due to limited time and resources, we only conducted our assessment during the dry season (August-October) using quadrat sampling and a 3.5cm corer to assess benthic infauna. However, this does not explain the difference in results as our study found significantly more genera and classes using a narrower sampling strategy. We, therefore, recommend more studies to identify microbenthic population fluctuations between wet and dry seasons as well as variation over longer time periods to gain a more comprehensive understanding of the temporal and spatial variation of macrobenthic biodiversity in dynamic rehabilitated mangrove ecosystems.

5.2. Impact of environmental factors on biodiversity

Temperature, salinity and rainfall are important environmental factors that strongly influence mangrove growth, survival and distribution. At a local level, the integrity and distribution of the mangrove ecosystem is also affected by soil, tides, geomorphology, mineral variability, soil aeration, wind, currents and wave action (Macintosh et al. 2002). We selected four comparable coastal villages to reduce the uncertainty stemming from these local environmental factors. However, regardless of the geographical similarity, the environmental factors did differ between the villages.

Our results presented slightly different salinity levels in the observed plots during the assessment period (August-October, i.e., dry season). Salinity is known to greatly influence mangrove growth, physiology,

Table 8
Macrobenthic species identified in the sampled plots of the four villages studied.

Class/Genus	Species	Sriwulan	Bedono	Timbulsloko	Surodadi
Bivalvia					
Enigmonia	*Enigmonia aenigmatica*	–	+	+	–
Saccostrea	*Saccostrea cucculllata*	–	+	+	–
Gastropoda					
Cassidula	*Cassidula aurisfelis*	+	+	+	+
	Cassidula nucleus	+	+	+	+
	Cassidula sp.	–	+	+	–
Cerithidea	*Cerithidea obtusa*	+	+	+	+
Neritina	*Dostia violacea*	–	+	+	–
Ellobium	*Ellobium aurisjudae*	–	+	–	–
Littoraria	*Littoraria melanostoma*	–	+	+	+
	Littoraria scabra	–	+	+	+
Melampus	*Melampus* sp.	–	+	+	+
Neritodryas	*Neritodryas subsulcata*	–	+	–	–
Onchidium	*Onchidium griseum*	–	+	–	+
Pythia	*Pythia scarabaeus*	–	+	–	+
Sphaerassiminea	*Sphaerassiminea miniata*	–	+	+	+
Tectarius	*Tectarius* sp.	–	+	+	+
Telescopium	*Telescopium telescopium*	+	+	+	+
Terebralia	*Terebralia sulcata*	+	+	+	+
Turbo	*Turbo crassus*	–	+	+	+
Malacostraca					
Coenobita	*Coenobita* sp.	–	+	+	–
Episesarma	*Episesarma versicolor*	–	+	+	+
Metaplax	*Metaplax* sp.	+	+	+	+
Metopograpsus	*Metopograpsus latifrons*	+	+	+	+
Paracleistostoma	*Paracleistostoma* sp.	+	+	+	+
Uca	*Uca dussumieri*	+	+	+	+
	Uca vocans	+	+	+	+
Polychaeta					
Capitella	*Capitella capitata*	–	+	+	–
Goniada	*Goniada* sp.	–	+	+	+
Nereis	*Nereis* sp.	–	+	+	+
Rhabditophora					
Limnostylochus	*Limnostylochus* sp.	–	+	–	+

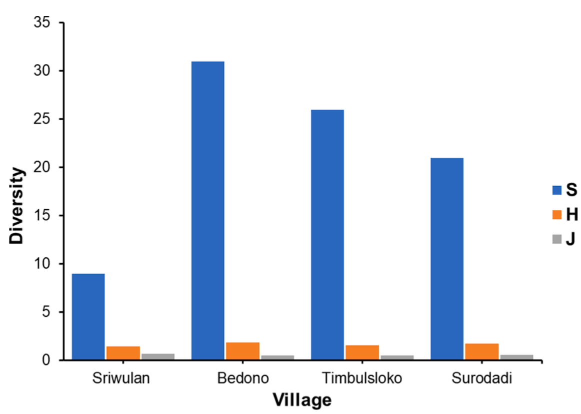

Fig. 3. Performance of the four villages in terms of macrobenthic diversity descriptors (S, H and J).

survival and diversity (Popp et al. 1993; Ball 1998; Ball 2002; Parida et al. 2004; Ye et al. 2005; Kodikara et al. 2018). Our analysis showed that salinity was negatively correlated with the seedling and tree richness, abundance, and diversity. These findings are in line with the result of Ball (1998), Devaney et al. (2021), and Kodikara et al. (2018) that highlighted the correlation of high salinity with low tree richness, low performance in seedling growth and high seedling mortality rate. *Rhizophora apiculata, Rhizophora mucronata, Avicennia marina, Avicennia officinalis, Bruguiera gymnorrhyza* and *Bruguiera sexangula* seedlings experience poor survival rate and stunted growth in salinity >30ppt (Kodikara et al. 2018). Furthermore, Kodikara et al. (2018) revealed that mangrove adaptation to salt varies with age and found better seedling performance under higher salinity after 15 to 20 weeks of age. The seasonal salinity fluctuation of the area designated for rehabilitation should, therefore, be taken into account when determining the time of planting, and the species and age of seedlings selected for planting.

Salinity level and sediment characteristics are among the most important environmental variables influencing macrobenthic abundance and diversity. Our assessment showed minor differences in salinity and sediment characteristics of the sampled plots except for a number of plots in Bedono and Timbulsloko. The sediment samples taken during the dry season were mostly dominated by the silt fraction. The salinity level and sediment composition and distribution may change along with increasing freshwater influx and sediment carried by the rivers during the rainy season (Wisha and Ondara 2017; Muskananfola et al. 2020a). Such changes will have a significant impact on the total abundance and diversity of benthic fauna in the sampling plots. Palmer et al. (2011) revealed decreasing benthic diversity in hypersaline condition of more than 30ppt. This finding corroborates the negative correlation between salinity and benthic diversity generated in our analysis since the average salinity in the sampling plots was above 30ppt. Furthermore, the fine sediment grains of the dominant silt fraction identified during our assessment is suggested to provide a larger surface to hold more organic matter (Uwadiae 2018). Organic matter is a major source of foods for macrobenthic fauna (Hyland et al. 2005; Uwadiae 2018). However, high concentration of organic matter in sediment (>3.5%) can decrease benthic abundance, biomass and diversity due to oxygen depletion and formation of toxic by-products (ammonia and sulfide) associated with decomposition of organic matter (Hyland et al. 2005; Uwadiae 2018; Fuller et al. 2021). Muskananfola et al. (2020a) recorded a relatively high concentration of organic matters in their sampled plots during dry and rainy seasons (an average of 14.6% and 14.9% respectively). Muskananfola et al. (2020a) further concluded that benthic diversity was lower when sediments were dominated by silt fraction. These explain the negative correlation

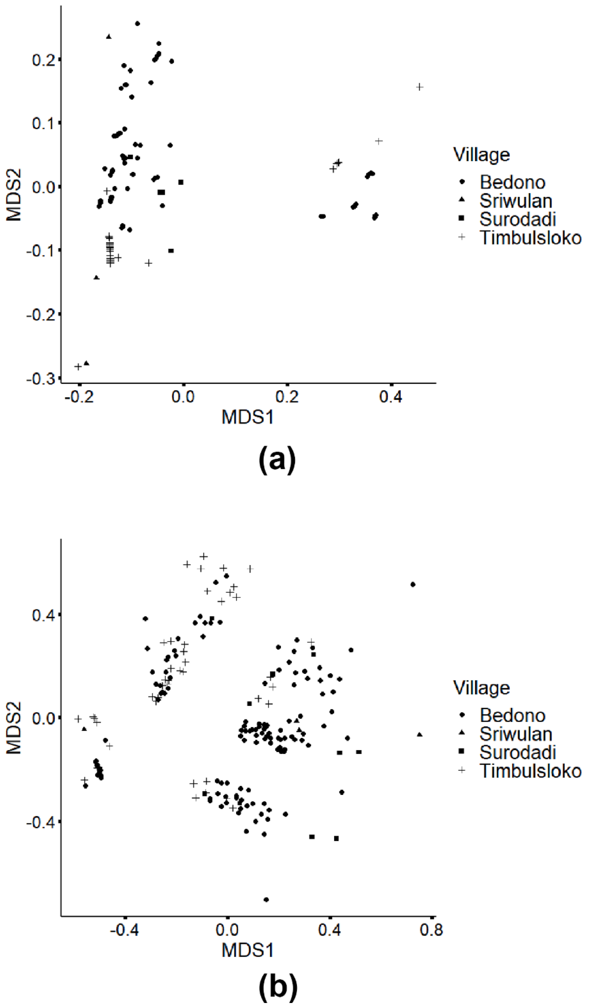

Fig. 4. MDS ordination of (a) abiotic variables (Stress = 0.03) and b) mangrove tree and macrobenthic faunal diversity (Stress = 0.16) at different sampling plots in the four villages studied.

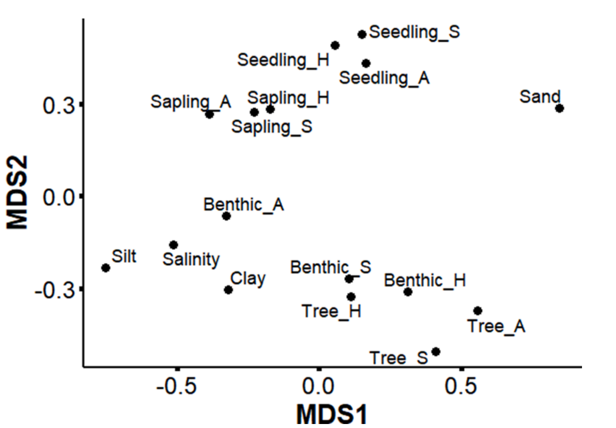

Fig. 5. MDS plot of Pearson's correlation between mangrove diversity and abiotic variables in the four villages studied.
S=species richness, *A*=Species abundance, *H*=Shannon diversity

(r=-0193, $p = 0.05$) between silt and benthic diversity in our analysis.

Furthermore, this study assumed the presence of several major natural disturbances (i.e. land subsidence and coastal erosion) in the four villages based on satellite imageries, local observations and interviews but without quantitative assessment of these disturbances. We believe that these can be of influence on mangrove survival rates. Recent studies on land subsidence and coastal erosion by Muskananfola et al. (2020b), Prasetyo et al. (2019), and Yuwono et al. (2018) provided evidence that support this assumption. According to Muskananfola et al. (2020b) Sriwulan, Bedono and the western part of Timbulsloko experienced higher erosion rates compared to Surodadi and the eastern part of Timbulsloko. Among the cause of this variation are jetty development in Semarang, land subsidence, and water depth/bathymetry. The construction of jetties in Semarang harbor (western side of Sriwulan) has been acknowledged to have caused a concentration of wave energy reaching the four villages. This results in high coastal erosion but a decreasing level of energy/severeness as the distance from the harbor increases (Marfai 2011; Muskananfola et al. 2020b). Prasetyo et al. (2019) outlined the influence of land subsidence on coastal erosion in Sayung. The level of subsidence differed with Sriwulan ranking highest (3.1cm) followed by Bedono and Timbulsloko (both 2.8cm), and Surodadi as the lowest (1.7cm) (Yuwono et al. 2018). The decreasing trend of subsidence rate from Sriwulan to Surodadi was correlated to excessive groundwater extraction in the nearby urban and industrial area of Semarang (Mahya et al. 2021). Furthermore, Muskananfola et al. (2020b) added that the water depth in Sriwulan and Bedono was higher (>2m) than in the other villages, which would allow the waves to run further landwards and hit the coastline of the two villages.

Severe coastal erosion appeared to have spurred the community, local government and other institutions to replant mangroves without proper pre-rehabilitation studies on these local environmental variables. The rehabilitation projects applied similar methods (i.e. using mainly relatively young *Rhizophora* seedlings of12 weeks or less), direct planting of propagules or seedlings protected by stakes and often similar timing at all selected sites, without any extra consideration of protective measures for the heavy coastal erosion. These differences in environmental factors should have been taken into account with site and species selection, planting techniques and additional technology for seedling protection. However, this clearly had not been considered as the rehabilitation projects applied similar methods. As a result, the survival rate of the replanted mangroves was higher in the landward zones, particularly around the ponds and settlements, and lower at the coastal sites that were more subject to wave and wind exposure.

The four studied villages are located adjacent to the highly populated and industrial area of Semarang, the capital city of Central Java. The factories near these villages have been continuously discharging their liquid waste in the rivers that flow to the villages' coastal water (Suprapti 2008; Supriyantini 2016). Furthermore, the villagers were also observed dumping their household waste directly in the mangrove areas and/or in the rivers that flow through mangrove areas in the four villages. Suprapti (2008), Supriyantini (2016) provided evidence of the high Chromium (Cr) and Cadmium (Cd) concentration in Sayung coastal waters. Chemical pollution, particularly accumulation and bio-transformation of toxic metals could be a significant factor limiting mangrove macrobenthic biodiversity (Maiti and Chowdhury 2013). However, we did not include such chemical contamination in our biodiversity analysis due to limited time and resources. Studies covering the issue are still lacking. Therefore, we recommend the topic for further research to get a more comprehensive understanding of the factors influencing biodiversity.

5.3. Impact of CBMM and governance aspects on effectiveness of mangrove restoration

Mangrove coverage, structure and biodiversity differed between the four villages (see Section 4.2). These differences were influenced by both environmental factors (i.e. different magnitude of coastal erosion) and rehabilitation and management strategies (i.e. rehabilitation scale, species selection, planting time, maintenance, and additional measures in response to coastal erosion).

The presence of several breakwaters combined with a larger scale of rehabilitation efforts, and regular (long term) maintenance appeared to have contributed to a larger mangrove area and higher seedling survival in Bedono, even though this village did not have more suitable conditions for rehabilitation. The combined strategies appear to have enabled natural regeneration resulting in higher vegetation diversity despite the high coastal erosion history in this village. The same was the case in Timbulsloko, where a combination of breakwaters and scale of rehabilitation efforts appeared to have positively influenced the area of restored mangrove cover and successful natural regeneration. Contrarily, the absence of breakwaters, lower rehabilitation efforts, irregular maintenance, and inappropriate planting time appeared to have resulted in a smaller restored mangrove area, high seedling mortality and lack of natural regeneration in Sriwulan. High seedling survival and a larger resulting area of restored mangroves in Surodadi can be partly attributed to the scale of rehabilitation, site selection and regular maintenance.

Our findings showed that a larger size of rehabilitated mangrove area corresponded to a more extensive habitat for the associated mangrove fauna e.g., invertebrates. Bedono has the most extensive mangrove area and also has the highest documented species richness, diversity and abundance of macroinvertebrates compared to the other villages. To the contrary, Sriwulan has the smallest mangrove area and the least diverse mangrove associated fauna. While cause and effect between total mangrove cover and observed diversity versus the CBMM decision-making processes cannot be proven conclusively, our sample results strongly suggest that the influence of decision-making with regard to the scale and timing of rehabilitation as well as maintenance of the rehabilitated ecosystems will affect the success of mangrove rehabilitation and resulting biodiversity.

The decision-making resulting from CBMM with regard to the scale of rehabilitation and other arrangements (e.g., village regulation, maintenance, construction of breakwaters) was greatly affected by the characteristics of community governance in each village (Table 3 Section 4.1). The partnership decision making process in Bedono gave equal bargaining power to both the community and external institutions in communicating and negotiating their goals, plans, knowledge and wishes. Such inclusion stimulated greater acceptance, support and commitment, crucial for the success of mangrove management. The top-down approach practiced in Sriwulan, on the other hand appeared to restrain the communities' ability to communicate their local knowledge, for instance on local weather pattems and associated risks, and wishes for more assistance to deal with high coastal erosion and seedling mortality. Such top-down decision-making processes reduced local support and commitment. It may cause scepticism, discouragement and even rejection.

Self-mobilised local collective action with genuine participation and a bottom-up decision-making process as applied in Surodadi appear to be an ideal model of community governance leading to sustainable results. Nonetheless, our analysis also shows the pivotal role that a strong and credible local leader can play to sustain this approach, as evidenced by a weakened collective action in this village after a leadership transition. In contrast, regardless of the top-down approach, the presence of an inspiring village leader may lead the community to achieve better mangrove management results as shown in Timbulsloko. Such leadership appeared, however, susceptible to conflicts of interest resulting in divisions in the community, social jealousy and withdrawal of support (Meilasari-Sugiana 2012a, 2012b).

6. Conclusions

This study analysed the effectiveness of different CBMMs for biodiversity by comparing different management and restoration strategies and their impact on the biodiversity of rehabilitated mangroves ecosystems in the rural, coastal villages of Sriwulan, Bedono, Timbulsloko and Surodadi on the north coast of Central Java. The overall comparison of CBMM seems to be highest in Bedono in terms of mangrove coverage and faunal diversity, whereas in Timbulsloko it was higher in terms of tree diversity. Surodadi distinguished itself with a higher seedling survival rate which we ascribe to have been influenced by the decisions related to site selection for rehabilitation and regular maintenance. The CBMM applied in Sriwulan was the least successful in terms of biodiversity impact, compared to the other villages.

The important factors contributing to the effectiveness of CBMM for biodiversity conservation were a) longer term-funding and maintenance, b) greater local acceptance for protective legislation, c) higher levels of public support d) use of more mangrove species, e) much larger spatial scale of mangrove restoration, and for highly eroded areas f) the presence of additional measures to reduce wave energy. This study highlights the important role of the type of community governance (bottom-up versus top-down) and (village) regulations in sustaining and maintaining the integrity of the restored mangrove forest and the associated biodiversity. Importantly, natural variability in environmental conditions should be taken into account when selecting rehabilitation sites, rehabilitation planning, species and planting techniques, and follow-up maintenance. Where this was neglected, it resulted in high mortality rates, as observed in Sriwulan. Village regulations have been a useful instrument in protecting the biodiversity of the rehabilitated mangrove ecosystems. This was suggested by the low occurrence of illegal logging and bird hunting incidents in the four villages. However, the rules alone could not prevent destructive fishing from occurring in all four villages, caused by a strong dependency of the local peoples' livelihood on fisheries. Therefore, efforts to restore and conserve mangrove biodiversity should consider the importance of poverty alleviation using development of mangrove-friendly alternative livelihood options (Debrot et al. 2020; Rejeki et al. 2021) and involve carefully designed public awareness activities and bottom-up planning processes for an optimal result.

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CRediT authorship contribution statement

Ekaningrum Damastuti: Conceptualization, Methodology, Funding acquisition, Resources, Investigation, Formal analysis, Data curation, Writing – original draft, Visualization, Project administration. **Rudolf de Groot:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Adolphe O. Debrot:** Visualization, Writing – review & editing. **Marcel J. Silvius:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2022.100202.

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