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How to restore mangroves for greenbelt creation along eroding coasts with abandoned aquaculture ponds.

Celine E. J. van Bijsterveldt*[1,2], Bregje K. van Wesenbeeck[3,4], Daphne van der Wal[1,5], Norma Afiati[6], Rudhi Pribadi[6], Benjamin Brown[7,8], Tjeerd J. Bouma[1,2]

1. NIOZ Royal Netherlands Institute for Sea Research, Department of Estuarine and Delta Systems, and Utrecht University, P.O. Box 140, 4400 AC Yerseke, The Netherlands
2. Department of Physical Geography, Utrecht University, P.O. Box 80.115, 3508 TC Utrecht
3. Unit for Marine and Coastal Systems, Deltares, 2600 MH Delft, The Netherlands
4. Department of Hydraulic Engineering, Delft University of Technology, 2600 GA Delft, The Netherlands
5. Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands.
6. Faculty of Fisheries & Marine Sciences, Diponegoro University, Semarang 50275, Indonesia
7. Research Institute for Environment and Livelihoods, Charles Darwin University, Darwin, Northern Territory 0909, Australia
8. Blue Forests, Makassar, Sulawesi, Indonesia

* celine.van.bijsterveldt@nioz.nl

1 Abstract

Globally, erosion of muddy tropical coasts that are dominated by aquaculture ponds, is an increasing problem. Restoration of mangrove greenbelts may counteract such erosion, by restoring the sediment balance. Hence, we aim to unravel the processes controlling natural mangrove regeneration in both "landward" (i.e., into aquaculture ponds) and seaward direction, using the fast eroding coastline of Demak (Indonesia) as case study. Firstly, we investigated which physical and chemical factors drive landward mangrove expansion by relating them to the presence/absence of mangrove seedlings in abandoned aquaculture ponds. Secondly, we investigated which physical parameters control seaward mangrove expansion by relating them to expansion and retreat at the sea-side of mature mangrove.

Landward mangrove expansion into abandoned aquaculture ponds was positively related to both emergence time (%) and sediment stability (i.e., shear strength), which are in turn both associated to bed level elevation and pond drainage. Surprisingly, there was no effect of soil chemistry. Seaward expansion of existing mangrove stands was strongly associated to foreshore morphology. Mangroves only expanded in the presence of an elevated mudflat, whereas the absence of a mudflat in combination with a concave (hollow) profile was associated with mangrove retreat. Our findings suggest that restoration of a mangrove greenbelt can be stimulated landward by improving drainage of abandoned aquaculture ponds. This enhances sediment stability and allows ponds to accrete. Seaward expansion can be induced by restoring foreshore morphology. Present results are discussed in the context of large-scale applications.

Key words: mangrove greenbelt, ecosystem rehabilitation, mangrove establishment, mangrove retreat, aquaculture, coastal erosion, foreshore.

2 Introduction

Mangrove ecosystems are widely recognized for their ecosystem services such as carbon sequestration, supporting fisheries, providing timber and coastline protection against erosion and flood protection from storm surges and tsunamis (Alongi, 2008; Barbier et al., 2011). However, over 35% of the world's mangroves worldwide have disappeared since the 1980s, mainly due to clearcutting and conversion to aquaculture ponds (Richards and Friess, 2016; Valiela et al., 2001). Tropical coastlines, where mangroves have been converted into aquaculture ponds, consequently lost the aforementioned ecosystem services (Thampanya et al., 2006). Especially the loss of sediment stabilization by mangroves is currently causing problems along multiple aquaculture coasts worldwide in the form of coastal erosion (Figure 1). Erosion of aquaculture areas can be as severe as several kilometers per year, putting coastal communities in danger (Van Wesenbeeck et al., 2015). Soft engineering solutions such as restoring mangrove greenbelts seems to be the best way forward to prevent further erosion (Van Cuong et al., 2015; Winterwerp et al., 2016, 2013). Mangroves attenuate both tidal currents (Mazda et al., 1997) and waves (Winterwerp et al., 2013), thereby diminishing erosion and enhancing sediment accretion (Chen et al., 2018), so that the mangrove greenbelt can keep up with sea level rise and hence offers a climate-proof protection against coastal erosion (Gedan et al., 2011; Lovelock et al., 2015).

Creation of a mangrove greenbelt is only possible by seaward extension onto the coastal mudflats, or by landward extension in abandoned aquaculture ponds. Unfortunately, merely planting mangroves without habitat restoration in either seaward or land-ward direction, has proven to be unsuccessful in many projects (Bayraktarov et al., 2016; Ellison, 2000; Lewis, 2005), with some projects showing mangrove establishment rates no higher than 10 per cent (Bayraktarov et al., 2016). Therefore, there is an urgent need to gain a basic understanding of which factors hamper mangrove establishment on both coastal mudflats and abandoned aquaculture ponds, to thereby gain insight in how to overcome thresholds for mangrove greenbelt creation by seaward or land-ward expansion. The coastline of North Java, Indonesia is an example of a region with extensive aquaculture and massive coastal erosion (Van Wesenbeeck et al., 2015). The recreation of a mangrove greenbelt is envisioned as the best solution to counteract erosion. The co-occurrence of small isolated mangrove stands with various rates of both sea-ward and land-ward expansion/retreat in patches along this coastline, make this area an ideal model system to study which factors drive mangrove greenbelt establishment in seaward (i.e., on tidal flats) or land-ward (i.e., in abandoned aquaculture ponds) direction (Figure 2).

Landward mangrove expansion into abandoned aquaculture ponds can be challenging because they can lack many of the favourable environmental conditions needed for establishment (Stevenson, 1997). Poor tidal flushing is often observed in abandoned ponds (Van Loon et al., 2016), and conditions that caused pond abandonment in the first place persist such as low oxygen concentrations due to eutrophication, high acidity, accumulation of toxicants like iron, aluminium (Raven and Scrimgeour, 1997; Stevenson, 1997), and methane (Strangmann et al., 2008). Although mangroves are generally relatively tolerant to toxins, this type of soil chemistry is known to hamper seedling establishment (Lewis et al., 2011; Strangmann et al., 2008). Hampered pond drainage can also lead to poorly consolidated mud (Fagherazzi et al., 2017), which may be unfavourable for seedling anchorage (Balke et al., 2011). Rehabilitation of mangroves in abandoned aquaculture ponds may thus be affected by various drainage related factors. Given this range of drivers, we aim to identify at the landscape scale the key-drivers restricting natural mangrove colonization in abandoned aquaculture ponds, using the coastline of North Java, Indonesia as case study.

In natural systems, sea-ward mangrove colonization tends to be episodic, only occurring if a sequence of favourable conditions follow each other in order to offer a Window of Opportunity for establishment (Balke et al., 2015, 2011). That is, a *i)* short inundation free period following propagule stranding, should be followed by *ii)* a wave free period to allow propagule anchoring and *iii)* sheet-erosion free period to allow seedling growth, for establishment to occur (Balke et al., 2015, 2011). The last two steps of these windows of opportunity can be affected by two key drivers: sediment stability and wave exposure. Understanding which of these drivers is more important for seaward mangrove expansion in aquaculture areas can help in choosing the right measures for ecological mangrove restoration. Using the coastline of North Java, Indonesia as case study, we aim to identify which drivers determine if a Window of Opportunity for mangrove establishment occurs versus when mangroves are more likely to retreat.

Summarizing, in the present study we aim to investigate the potential for mangrove greenbelt creation along eroding aquaculture coasts by elucidating (1) what processes are the key-drivers that facilitate or hamper mangrove colonization in abandoned aquaculture ponds (i.e., landward expansion of mangroves) and (2) which factors drive expansion or retreat at the seaward mangrove front (i.e., seaward expansion of mangroves). We hypothesize that the main drivers controlling (1) the landward natural mangrove establishment in abandoned aquaculture ponds are either (1a) unfavourable chemical sediment properties like high acidity or (1b) poor sediment consolidation reducing seedling stability (Figure 2). We hypothesize that the main factors controlling (2) seaward mangrove establishment are either (2a) the presence /absence of wave-sheltering foreshores or (2b) sediment consolidation, with poor consolidation reducing seedling stability and thus survival (Figure 2).

3 Methods

3.1 Site description

Hypotheses were tested along short transects in abandoned aquaculture ponds and mangrove stands along the coastline of Demak, Central Java, Indonesia. The coastline of Demak is a region with a history of extensive aquaculture, with a tidal range of approximately 1 meter and dominated by waves during the north-west monsoon in the wet season from November until

February (MMAF, 2012). The coastline of Demak consists of alluvial deposits and used to harbour a mangrove-mud system several centuries ago according to old colonial maps. Since then, mangroves have been converted to rice paddies and later to aquaculture over the last century. The whole coastal plain 5 km inland bordered by the main road from Semarang to Demak and ranging from the city of Semarang, up to the river delta of the Wulan river was covered with aquaculture ponds (50*200 m) which were merely separated by pond bunds. From the year 2000 onward erosion has led to loss of large areas of aquaculture (Marfai, 2011; Van Wesenbeeck et al., 2015). Despite rapid erosion of Demak's coastline, some abandoned aquaculture ponds start showing mangrove recruitment. The vision of the government is to expand these mangrove stands to a mangrove greenbelt along the coastline, to stabilize the coast and to protect the villages and persisting aquaculture from further erosion. However, mangrove recruitment that is currently taking place in abandoned aquaculture ponds seems patchy even though propagule limitation does not seem to be an issue, with some aquaculture ponds showing much better recruitment then others, hampering landward mangrove expansion (Figure 3). The few mangrove stands that have appeared along the former coastline are of variable stability in terms of seaward expansion or retreat. Stands show seaward expansion in some places, while they show retreat due to tree mortality at the coastline in other places (Figure 3**Error! Reference source not found.**). In this study, we use these contrasting mangrove states to analyse which processes control landward and seaward mangrove expansion along eroding aquaculture coastlines.

3.2 Mangrove recruitment in abandoned aquaculture ponds

3.2.1 Data collection in abandoned aquaculture ponds

The hypothesis that mangrove colonization in aquaculture ponds is driven by processes related to drainage was investigated during a field campaign in which eleven abandoned aquaculture ponds were assessed for their suitability for seedling recruitment (Figure 4).

3.2.1.1 Field study design

The ponds were selected based on abandonment, a comparable surface elevation at first sight and a variable seedling recruitment at first sight. Ponds were considered clearly abandoned when there was no sluice and at least one pond bund was absent. Data was collected in each of these ponds over the course of five weeks in September 2015, before the start of the wet season. Measurement stations were aligned in the pond along a transect starting at the most seaward pond bund in the shallowest area of the pond. The transect ran from the water level at low tide from the north-west pond bund and stations were spaced three meters apart across the pond until the creek (if that was present) to cover the full environmental gradient of the pond (Figure 4). Firstly, seedling density of *Avicennia* spp. was recorded in 1 m^2 quadrants at five stations in each pond as a response variable and indicator of suitability for seedling recruitment. Seedlings were defined as all mangrove plants that were below 1 m in height. At each station several explanatory variables were measured: (a) inundation time, (b) soil redox potential, organic carbon, sulphide concentration and pH to assess the soil chemistry and (c) soil water content, bulk density, shear strength and median grainsize to assess soil stability.

3.2.1.2 Collection of inundation time data

Inundation time was measured by Sensus Ultra dive data loggers (ReefNet Inc.), which were deployed in each pond for a period of two to three days. A reference water level logger was deployed in the sub-tidal area to account for the tidal fluctuations during the whole field campaign. Tidal information obtained from each pond logger was then compared to the tidal information logged by the reference logger during that period (A1). The vertical position of the pond loggers compared to the subtidal reference logger was determined by overlaying the maximum peak of the tidal curve obtained in each pond to the corresponding peak in the tidal curve of the reference logger. Maximum tidal peaks were chosen as a parameter because average water level could not be determined for sites situated at intertidal level. The vertical position of each pond logger compared to the reference logger was then used to extrapolate the number of times the pond logger was inundated over the whole field campaign. This extrapolation causes some uncertainty in actual inundation times per pond, but enabled us to reuse loggers and thereby include multiple ponds and sites and minimize uncertainties due to local pond and site differences. Submergence time (defined by the width of a peak in the tidal curve) measured by the pond logger was calculated to an average submergence time per day. Average submergence time per day was estimated for each pond-station by relating the relative surface elevation of each station along a transect to the relative surface elevation of the pond-logger (A2). The relative position of each station compared to the pond loggers was measured with a laser (Spectra precision® LL300N). Relative surface elevation per site obtained with the laser could then be standardized to the average submergence time per day during the field campaign.

3.2.1.3 Collection of soil chemistry and soil stability related parameters

All chemical and physical soil parameters were collected under water logged conditions of the soil, around average water level in the tidal cycle. pH and redox potential were measured simultaneously at 10 cm sediment depth with electrodes (pH-electrode SentixSp, Electrode SenTixORP-T900) and a portable multimeter (multi 3430, WTW). Furthermore, shear-strength was measured with a vane (Geonor H-60 vane borer with tailor made head (h: 100 mm D: 80 mm)) at each station to get an indication of the bed consolidation. All other soil parameters were obtained through sediment sampling. Organic carbon content, bulk density, water content and median grainsize were determined from sediment samples, from the upper 5 cm soil at each station. Sediment samples were collected with a decapitated 100 mL syringe and stored in a fridge until further analysis. Sulphide concentration was determined from 3 mL soil samples that were collected at 5 cm depth in the sediment and were instantly stored in 20 mL Zinc Acetate (ZnAc) 2% solution to prevent oxidation of sulphide. Sulphide concentrations were determined according to a sulphide assay protocol (Trüper and Schlegel, 1964). Wet sediment samples were placed in a container with known volume, weighed and placed in a stove (105 ℃) for at least 24 hours and weighed again to determine bulk density and water content within six weeks after collection (samples had been stored at 4 ºC). Dry samples were then placed in a 350 ℃ stove for 24 hours and weighed again to determine organic carbon content. Finally, grainsize distribution of freeze-dried subsamples was determined with a Malvern (Mastersizer 2000, Malvern Instruments).

3.2.2 Statistical analysis of abandoned aquaculture pond data

To test the effect of the different soil chemistry and stability related parameters in aquaculture ponds on mangrove recruitment we used a redundancy analysis (RDA) in R package (R version 3.4.4) vegan. This ordination technique shows how much of the variation in mangrove recruitment (seedling density) is explained by the explanatory parameters measured (inundation time, soil redox potential, organic carbon, sulphide concentration, pH, water content, bulk density, shear strength and median grainsize), and to analyse how the explanatory variables relate to each other.

3.2.2.1 Data preparation and transformation

Prior to the redundancy analysis, two stations with a missing value in pH were omitted from analysis. Seedling density as a response variable was highly zero-inflated and could therefore not be transformed to normality; instead this variable was categorized into three ecologically meaningful classes: “no seedlings present”, “one seedling present”, “multiple seedlings present” and added to the ordination analysis as an untransformed response variable matrix with three binary variables.

3.2.2.2 Testing collinearity of explanatory variables

All explanatory variables were tested for collinearity prior to the redundancy analysis, by calculating their variance inflation factors (VIF). VIF values are derived from the R^2 values after regression of each individual variable against all other variables (Legendre and Legendre, 2012). VIF scores of all explanatory variables were below 3, the most conservative threshold value for collinearity mentioned in literature (Zuur et al., 2010). None of the explanatory variables was therefore omitted from further analysis based on collinearity.

3.2.2.3 Redundancy analysis on seedling density classes

A redundancy analysis (RDA) was run to investigate the difference between stations based on classes of seedling density and how the measured variables explain those differences. The analysis was run on the seedling density classes' matrix and explanatory variable matrix. A permutation test was performed 999 times to test if this relationship between the matrix of explanatory variables and the matrix of response variables was statistically significant (Borcard et al., 2018).

3.3 Expansion and retreat in sea-side mangrove stands

3.3.1 Data collection in sea-side mangrove stands

To understand what parameters related to sediment stability and wave-exposure drive seaward mangrove expansion and mangrove retreat in existing mangrove stands along Demak's coastline, we used a combination of field-derived data and Geographical Information Systems (GIS) derived data.

3.3.1.1 Field study design and collection of sediment stability related parameters in the field

Five expanding mangrove sites and five retreating mangrove sites were randomly selected in the study area (Figure 4). All mangrove stands within a one hour trip by boat from our field station that showed mangrove expansion or mangrove retreat were included as possible sites for a transect. We defined expanding mangrove stands as stands with seedling recruitment seaward of the stand and progressively older trees towards the land. We defined retreating mangrove stands as mangrove stands characterized by uprooted mangrove trees along the seaward edge. At each site, several sediment stability related parameters were measured during the same field campaign in September 2015. Parameters were collected along transects running from 3 meters inside the mangroves stand, towards the subtidal zone (Figure 4). Soil water content, bulk density, shear strength and median grainsize were measured at each station in the field as explanatory variables related to sediment stability. Seedling presence was measured in 1 m^2 quadrats at each station as one of the mangrove response variables.

3.3.1.2 Collection of wave exposure related parameters

3.3.1.2.1 Field derived parameters

At each of the aforementioned transect stations, mudflat elevation relative to a local water level logger was measured, from which submergence time and mudflat-slope were derived as local explanatory variables related to wave exposure. Waypoints of each station in the field were marked in a hand held GPS (garmin etrex) so that GIS parameters could be extracted and added to the dataset.

3.3.1.2.2 GIS derived parameters

To further understand drivers of mangrove retreat and expansion along the coast as a result of wave exposure at land-scape level, several additional explanatory variables were obtained by GIS analysis. Mudflat width from each sampling station at low tide, outer boundary shelter width (for instance sand lenses along the coast and sea walls), sand bank width at low tide, and wind fetch at low tide in north-west direction were chosen as proxies for wave exposure.

In order to obtain these wave exposure proxies by GIS analysis, two Copernicus Sentinel-2 MSI satellite images, that were atmospherically corrected using the Sen2cor module in SNAP software, were used to analyse the effect of potentially sheltering geomorphological features such as sand banks and mudflats on the mangrove cover in Demak. The images have a 10 m spatial resolution. Two images with low cloud cover were selected. The first image was acquired at low tide (-24 cm relative to MSL) with an acquisition date close to the period of the field campaign (acquisition date: 7 Oct 2015). These selection requirements ensured that dynamic wave exposure related features such as sand bars and mudflats would be visible and would be located (close to) the position they had during the field campaign. The second image was selected based on a similar tidal level as the first image (-23 cm relative to MSL) and an acquisition date shortly after the stormy wet season (15 January 2016) to detect relevant mangrove cover change related to the explanatory variables as measured during the field campaign before the wet season. Cloud and cloud shadows were flagged in each image using QSC values (produced by Sen2cor). The satellite images were then reprojected to UTM49S. The NDVI, i.e. Normalized Difference Vegetation Index, was calculated based on surface reflectance in the red (R) and in the near-infrared (NIR) spectral bands of the images following (NIR-R)/(NIR+R). These NDVI rasters were then classified into 3 classes for fetch analysis: NDVI > 0.3 = vegetation, NDVI < -0.04 = water, -0.04<NDVI<0.3 = potential geomorphologic shelter (exposed sediment). These cut-off values resulted in classes that corresponded to land cover states as observed in the field, except from seedling covered mud-flats which could not be distinguished from bare mudflat.

The distance to sheltering features in north-west direction from each sampling station was obtained by analysis of lines drawn in north-west direction from each sampling station using the bearing distance to line tool in ArcGIS. Underlying classified raster values (vegetation, water and exposed sediment) were then extracted at points with a 7.07 meter interval (i.e., half the diagonal pixel length) along each bearing line. Resulting lines contained alternating values of mangrove, mud and water depending on the geomorphology obtained from the satellite images (A3). Puddles of water on the mudflat and small boats in the water were excluded from the analysis using a smoothing algorithm (A4). This smoothing process was done by assigning the raster value found in the majority of five cells: the cell of interest and two cells before and after the cell of interest along the bearing line (A4). Small shifts in mudflat and water border could not be avoided with this method (A4). Therefore, the smoothened bearing line values were only used to derive the explanatory variables mudflat width, sand bank width and wind fetch length. The width of each of these parameters was obtained from the location of border cells (e.g. water-mud transition) relative to another border cell of interest. For instance, fetch length was determined by subtracting the distance from the start of the bearing line of the outer water-to-mud transition from the minimum distance of mud-to-water transition along the same bearing line. Fetch length of more than 2 km from the coast was considered infinitive fetch with maximum wave exposure. Mangrove vegetation retreat and expansion between 2015 and 2016 were derived from the unsmoothed NDVI classification raster as response variables.

3.3.2 Statistical analysis of sea-side mangrove stand data

For statistical analysis of the factors that could explain mangrove expansion seaward, we again used a redundancy analysis. Mangrove expansion parameters from both the field (seedling presence) and GIS (mangrove expansion and mangrove retreat) were used as response variables, because seedlings could not be detected in the satellite images. Sediment stability related parameters and wave exposure related parameters from the field and GIS analysis were also all considered for the analysis as explanatory variables.

3.3.2.1 Data preparation

Prior to analysis, six missing values in the shear strength data collected at retreating mangrove sites were substituted with the maximum measured value of the shear strength values in the total dataset. This substitution was chosen because the missing values were a result of extremely high soil impenetrability due to numerous roots and shell fragments in the sediment that could have damaged the vane head. Using the maximum measured shear strength instead is justified at these sites, as these sites clearly had an extremely high shear strength and no reliable missing value regression could be made. Although the use of a shear strength value that is lower than the actual shear strength likely causes an underestimation of the effect of shear strength on mangrove retreat. Finally, all stations that lacked information on sediment variables were omitted from the analysis resulting in a full dataset with 29 stations, divided over 10 cross-shore transects with one station inside the mangrove forest, one station at the mangrove edge and one subtidal station.

3.3.2.2 Omission of collinear variables

VIF analysis was run on the entire explanatory data matrix to test for collinearity among the explanatory variables for seaward mangrove expansion. VIF analysis showed that the majority of VIF values were above 3, with relatively high VIF scores for median grainsize (4.5), soil water content (7.6), bulk density (3.4), maximum shelter at low tide (5.9), sand bank width (16.6), wind fetch at low tide (9.0), and mudflat shelter at low tide (20.9). We therefore decided only to include shear strength as most relevant variable for the "stability hypothesis", and to include slope and mudflat width as most ecologically relevant field and GIS derived variables for the "wave exposure hypothesis".

3.3.2.3 Redundancy analysis on mangrove states

The RDA was then performed on a response variable matrix composed of seedling presence in September 2015 (measured in the field), mangrove expansion and mangrove retreat based on NDVI satellite data between October 2015 and January 2016. The response variable matrix with these three response variables was then subjected to a relativity transformation to obtain relative mangrove response values per site. This transformation ensured that sites with both GIS derived mangrove expansion values and seedling presence values from the field, obtained a total score that was equal to sites with just mangrove expansion or seedling presence, as these three response variable combinations are ecologically similar. Finally, a permutation test was performed again to test if the explanatory variables (slope and mudflat shelter) explained the distribution of response variables significantly.

4 Results

4.1 Mangrove recruitment in abandoned aquaculture ponds

The redundancy analysis showed that all soil stability and soil chemistry parameters together, explained 16% (Ezekiel adjusted R^2) of the variation in seedling density in abandoned aquaculture ponds (F = 2.1, p = 0.03, df = 9). Furthermore, only environmental variables with their major component along the horizontal axis significantly explained seedling presence in abandoned aquaculture ponds (F = 20.1, p = 0.02, df = 1) (Figure 5). Despite the non-significant relation between the vertical components and seedling density class, we also plotted these environmental variables in order to provide basic insight in the correlations among environmental factors (Figure 5). The results show that mainly high soil stability and low submergence time are plotted along the horizontal axis and are therefore related to seedling presence. Especially high soil stability (shear strength) correlates with stations where multiple seedlings were found in abandoned aquaculture ponds (Figure 5). Meanwhile, all soil chemistry related parameters such as redox potential, sulphide content and pH are aligned with the vertical axis of the plot and are therefore no significant predictors of seedling presence in abandoned aquaculture ponds. Finally, many of the measured explanatory parameters show expected relations among each other, such as high shear strength with low soil water content and high redox potential with high sulphide concentrations (Figure 5).

4.2 Mangrove expansion and mangrove retreat along the coast

To understand what processes are most important for natural seaward mangrove expansion in front of abandoned aquaculture coasts, we analysed the effect of parameters related to wave exposure (mudflat width and slope) and of soil stability (shear strength). The redundancy analysis revealed that 33 % (Ezekiel adjusted R^2) of the variation in mangrove expansion and retreat along the coastline can be explained by the wave exposure and soil stability parameters that we analysed (Figure 6, F = 3.8, $p < 0.001$, df = 5). Sites with mangrove expansion (stations with either seedling presence in the field or NDVI increase over the wet season) generally had low slopes (0-2 *cm* m^{-1}) or even negative sloping foreshores, which means that they were protected from waves by a mudflat or sand bank with a higher surface elevation than the bed level at the station itself. Mudflat width also showed a clear positive correlation with mangrove expansion over the wet season of 2015-2016. Conversely, stations where mangrove retreat had taken place or where no vegetation change had occurred had moderate (2-5 cm m^{-1}) to steep (5-18 *cm* m^{-1}) foreshores, which would make those sites more vulnerable to breaking waves. Finally, sites where mangrove retreat occurred generally had a higher shear strength than sites with mangrove expansion (Figure 6), indicating that enhanced soil stability is not a main driver of sea-ward mangrove expansion.

5 Discussion

The rapid decline in coastal mangrove areas, caused by clear-cutting, land-use change to cities and aquaculture ponds and eventually coastal erosion, drives an increasing attention for mangrove conservation and restoration. For proper mangrove restoration, a better understanding of factors that drive mangrove recruitment is essential. The current research focusses on main drivers limiting mangrove expansion landward and seaward separately. Present findings are discussed in the context of coastal management aimed at mangrove greenbelt creation to counteract erosion.

5.1 Method uncertainty

In general, the redundancy analyses of mangrove restoration state in aquaculture ponds and coastal sites revealed various factors that could significantly explain those states. In hindsight, current correlations could have been stronger due to some uncertainties in our response variables. The field dataset of seedling density contained a large number of zero's. The chances of including a seedling in the quadrat through random sampling per station was low due to the combination of a relatively small quadrat size and a relatively low amount of seedlings. We therefore ended up with a value of zero seedlings in some stations where there were actually some seedlings around, but that just did not happen to fall in our quadrat. Increasing the number of quadrat measurements per station, or increasing the quadrat size could have decreased the zero-inflation of our dataset and could potentially have made the present correlations stronger. In addition, the response variables that were quantified using the Sentinel-2 satellite images had a spatial resolution of 10 meters, which means that lateral changes in mangrove cover smaller than ca 10 meters could not be detected. For mangrove expansion, this uncertainty was minimized by measuring seedling presence in the field. For mangrove retreat, the use of non-freely available satellite images of higher resolution could have detected smaller changes in mangrove retreat, where mangrove state was now classified as stable. This may have made the present correlations stronger, although one may wonder how important it is to detect changes of less than ten meter over a single wet season. Despite this relative course 10 m resolution, the explanatory variables that we chose did explain the variation in mangrove states significantly, yielding meaningful management implications.

5.2 Mangrove recruitment in abandoned aquaculture ponds

We hypothesized that landward natural mangrove recruitment in abandoned aquaculture ponds would be driven by processes related to either (1a) unfavourable soil chemistry or (1b) poor soil stability. Our results showed that soil chemistry related parameters do not seem to be important predictors of seedling establishment in abandoned aquaculture ponds. Relations among chemical parameters were as expected, e.g. a high pH seems related to a more positive redox potential and highly negative redox values are correlated with sulphidic conditions (Figure 5). However, all chemical soil parameters were aligned with the vertical RDA axis and could hence not be clearly related to seedling abundance (Figure 5). The fact that the soil chemistry parameters measured in this study did not influence seedling abundance significantly is somewhat surprising, as nutrient rich effluents of active aquaculture have been known to cause eutrophication (Nóbrega et al., 2014) and unfavourable conditions for mangrove establishment (Strangmann et al., 2008). The redox values and pH values found by Strangmann et al. (2008) (i.e., redox: -276 mV - 294.0 mV, pH: 7.6 - 8.3) and Nóbrega et al. (2014) (i.e., redox: 36 mV – 256 mV, pH: 6.9 - 7.4) in sediment near shrimp farms are variable and cover a large range of values including values found in our study (Table 1). Both studies show that soil chemistry is different in impaired mangroves vs. pristine mangroves, but especially in terms of phosphate (Nóbrega et al., 2014) and methane (Strangmann et al., 2008). The pH does not actually appear to be much different between such sites in these and our studies. Redox potential does seem to be lower in sites near shrimp farms in both studies and especially redox potential values found in Strangmann et al. (2008) are comparable to values measured in our aquaculture ponds (Table 1). However, these values can also be found in their pristine mangrove sites (Strangmann et al., 2008). The large variation in redox potential found within sites (even pristine sites) in these studies and the small explanatory power of these parameters on seedling presence found in our study, suggest that pH and redox potential are possibly poor indicators for mangrove establishment.

Our results do show a much clearer picture with regards to the effect of soil stability on seedling density in abandoned aquaculture ponds. Shear strength showed a clear positive correlation with high seedling abundance (Figure 5) and seems to be related to low water content and high median grain size from the redundancy analysis. The grainsize analysis showed that abandoned aquaculture ponds are generally filled with muddy sediment of a low grain size and that there was little variation in grainsize overall (Table 1). Sediment of such a low grainsize is usually slow in consolidation, as the particles are very light and are therefore easily resuspended. Slow consolidation can result in a liquid mud layer which has a high water content and can easily be mobilized (Winterwerp et al., 2012). The low critical bed-shear stress of fine sediment

(Mitchener and Torfs, 1996) is known to offer very little stability to mangrove seedling establishment (Balke et al., 2011; Hu et al., 2015). Low shear strengths found at the stations where seedlings were absent versus high seedling abundances at locations with high sediment shear strengths, seem to be in accordance with these studies. The fact that shear strength of mud is closely related to water content complies with Fagherazzi et al. (2017), who found that the erodability of mud-flats significantly decreases with increasing evaporation.

Our results furthermore suggest that decreasing submergence time in aquaculture ponds also favours seedling presence in abandoned aquaculture ponds, as seedlings were never found at low-lying stations and only occurred at locations with an inundation period of less than 40% of the day. These findings are in accordance with the vegetation classification per hydrological class from Watson (1928), and modified to inundation time per day by Van Loon et al. (2016), in which *Avicennia* species occur at inundation durations of 400-800 minutes per day (or 28-56% per day). Although mature mangroves are well adapted to flooding, seedlings are vulnerable to prolonged inundation times and have shown increased mortality due to flooding in various species (Krauss et al., 2008). Increasing bed level elevations in abandoned aquaculture ponds could therefore both increase low inundation habitat surface area for seedlings and improve soil stability.

Overall, present findings suggest that seedling establishment in abandoned aquaculture ponds could be enhanced both by enhancing soil stability and decreasing inundation stress through bed level accretion. Providing there is enough sediment available in the water column, both aspects may be increased through improvement of hydrological connectivity, as tidal flooding is needed to deliver sediment while good drainage is needed to obtain bed-level stability. Hydrological connectivity can for instance be improved through breaching of the sea-ward pond bund, or digging drainage canals after a pond has been abandoned (Figure 7). These measures have indeed been proven effective for mangrove restoration in abandoned aquaculture ponds, and have as additional advantage that they also improve propagule distribution in areas where that is a limiting factor (Lewis, 2005; Proisy et al., 2018; Van Loon et al., 2016).

5.3 Mangrove expansion and mangrove retreat along the coast

We hypothesized that once a mangrove stand has developed, e.g. in an abandoned aquaculture pond, further seaward expansion would be mainly driven by either (2a) the presence of sheltering features on the foreshore that attenuate waves or (2b) by sediment consolidation, with poor consolidation reducing the expansion. In line with hypothesis 2a, our results show that mangrove retreat along the coast is indeed found at locations with minimal shelter from wind induced waves. That is, areas with mangrove retreat had a minimal mud-flat width, as quantified from Sentinel-2 satellite images, and field observations showed that transects with mangrove retreat generally had steep slopes (Figure 6). In contrast, mangrove expansion by young mangrove trees that could be observed from Sentinel-2 images was found behind wide mud-flats and in areas with a level to negative slope (Figure 6). A negative slope measured along expanding mangrove transects, indicates that the young mangrove trees were literally sheltered by mud-flats with a higher surface elevation seaward of the mangrove border. Stations that did not show mangrove expansion based on NDVI values, but did show seedling recruitment in the field were found at places with low to level slopes from sea to land. This could be explained by the fact that natural seedling settlement can only take place if a window of opportunity occurs (Balke et al. 2011, 2015). A Window of Opportunity requires both a high area of the mudflat, where an inundation-free period may occur following propagule stranding, and a sheltered area so that a wave-free period enables emerging seedlings not to be dislodged (Balke et al., 2015, 2011).

The importance of foreshore morphology as a driver of vegetation dynamics is in accordance with findings of Winterwerp et al. (2013), Hu et al. (2015) and Bouma et al. (2016). Winterwerp et al. (2013) observed that in the mangroves of Surinam, concave (hollow) profiles concentrate wave energy, thereby causing a positive erosional feedback loop. In contrast, convex profiles, created by migrating mud banks from the Amazon (Anthony et al., 2010), slowly dampen the waves allowing for sediment deposition inside the mangroves and thus for a positive accretion loop (Winterwerp et al., 2013). Hu et al. (2015) modelled these processes to predict the window of opportunity for salt marsh expansion in the Netherlands with a model in which hydrodynamic forcing was incorporated on top of inundation time. Both slope and bathymetry profile had significant influence on salt marsh width (Hu et al., 2015). Slope itself is an important driver of salt marsh width, as different slopes inherently create different amounts of settlement space at a certain tide level. However, mudflat profile along transects with the same slope proved to impose large differences on salt marsh width as well, predicting an increase of 300% salt marsh width along a transect sheltered by a convex mudflat compared to a salt marsh sheltered by a concave mudflat with the same 1/200 slope (Hu et al., 2015).

In contrast to the expected outcome of hypothesis 2a, our second hypothesis (2b) “sediment stability causes seaward mangrove expansion through enhanced seedling stability” was not confirmed by our shear strength measurements. Sediment stability has been reported as an important limit to sea-ward mangrove expansion (Balke et al. 2013a, 2013b, 2015). This usually goes hand in hand with wave exposure: the more hydrodynamic forcing, the lower the sediment stability, and therefore the lower the seedling stability. Sediment stability was observed to be directly related to foreshore width (Bouma et al. (2016). In all these studies, the sediment stability was however measured as bed-level changes over time. In contrast, we measured sediment strength using a shear vane. This method is widely used (Chen et al., 2012; Hauton and Paterson, 2003; Khan and Kostaschuk, 2011; Serota and Jangle, 1972; Winterwerp et al., 2012), as shear-vane observations typically correlate well with physically measured critical erosion threshold (Grabowski, 2014). However, this indirect measurement, makes that our observations cannot be directly compared to studies where the sediment stability was measured in terms of bed-level change over time. Nevertheless, it is surprising that we found high shear strengths to be positively correlated with retreating mangroves (Figure 6). Shear strength along the coast seems to have been driven by grainsize rather than consolidation, as the variation in grainsize along the coast was much more pronounced than was the case in the aquaculture ponds (Table 1). In our retreating mangrove stands, the steep foreshore can have resulted in breaking waves on the mangrove border, which can cause resuspension of small sediment particles and leaving sandier sediment (with a higher shear strength) behind. Alternatively, previous erosion may have exposed a deeper stronger soil layer. Most importantly however, although experimental studies have shown that the absence of bed-level dynamics (i.e. soil stability) is good for seedling establishment (both for mangroves and salt marshes (T. Balke et al., 2013; Bouma et al., 2016)); at our field sites foreshore morphology appears to be the most important driver of seaward expansion.

5.4 Landward versus seaward mangrove expansion for green-belt creation

The difference between abandoned aquaculture ponds and coastal mangrove restoration sites in importance of shear strength for seedling stability has not been demonstrated before. In aquaculture ponds, we found that stability related soil-parameters like shear strength, besides submergence time, mostly seem to determine where seedlings grow (Figure 5). Contrastingly, in more exposed conditions along the seaside, high shear strength was correlated with mangrove retreat (Figure 6). These results show that increasing soil stability itself through bed level increase and improved drainage (as the results from the aquaculture ponds alone suggested), does not necessarily result in more seedling establishment. Along the coastline, management efforts should instead focus on creating and conserving wave sheltering features, such as sand banks, mudflats or artificial wave attenuators (Figure 7). Understanding such main driving processes of the ecosystem is important because it has implications for management. The patchy mangrove fringes and states that we found in our research area are common for many former mangrove coasts that have been converted to aquaculture ponds, such as e.g. in Vietnam (Van Cuong et al., 2015) and in Thailand (Winterwerp et al., 2013). In addition, the aquaculture ponds in our study area are very common all throughout Asia in terms of hydrological connectivity and size. Of course it cannot be excluded that in some regions soil chemistry might be a more important stressor for mangrove recruitment, e.g., when aquaculture practices have been industrialized (Stevenson, 1997) or herbicides like agent orange have been used in large quantities (Hong and San, 1993). However, when such very specific historical local land use effects are absent, present findings offer insight in the main drivers that may be manipulated for mangrove restoration projects along many Asian coastlines.

6 Conclusions and management implications

Our findings suggest that mangrove recruitment can potentially be initiated in old aquaculture ponds if: (1) The bed level of an old pond exceeds mean water level so that inundation times are below 40% per day and (2), sediment stability is sufficient. Both beneficial conditions for mangrove establishment in aquaculture ponds could be improved through promotion of pond drainage after abandonment, so that sediment accretion and consolidation can take place (Figure 7). For management purposes and greenbelt restoration in aquaculture areas, it is therefore important to keep monitoring if the bed level is increasing after breaching of the pond bunds until the desired bed level is reached, and investigate the cause of insufficient sedimentation if the bed-level does not increase after breaching of pond bunds.

With regard to maintenance of newly established mangrove stands for greenbelt restoration, our findings suggest that expansion and retreat is primarily related to the shelter provided by the foreshore. Convex mudflat profiles seem to promote mangrove expansion and concave profiles without sheltering mudflats seem to induce mangrove retreat (Figure 7). To maintain restored mangrove stands along former aquaculture coasts, it is therefore important to monitor the state of the foreshore and understand the processes that cause convex and concave shore profiles.

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Table 1 Descriptive statistics of all parameters measured related to landward expansion in aquaculture ponds; and parameters measured in the field and derived from GIS related to seaward expansion of mangrove stands.

Parameter	n	Minimum	Average	Median	Max	Standard Deviation
Related to landward mangrove expansion (in aquaculture ponds)						
pH	53	6.6	7.2	7.1	8.0	0.3
Redox potential (mV)	53	-226.3	-146.0	-153.1	-29.5	46.8
Sulphide concentration (µM)	53	395.3	2484.3	1366.4	11181.3	2129.7
Median grain size (µm)	53	5.1	6.0	6.0	7.7	0.4
Soil water content (%)	53	54.4	59.8	59.8	65.5	2.5
Organic carbon content (%)	53	6.8	9.7	9.5	13.8	1.5
Wet bulk density (g cm^{-3})	53	1.2	1.4	1.4	1.7	0.1
Shear Strength (Pa)	53	0.3	1.0	1.0	2.4	0.4
Time submerged per day (%)	53	5.1	36.0	24.9	100.0	28.5
Seedling Density (m^{-2})	53	0.0	1.3	0.0	16.0	3.1
Related to seaward mangrove expansion (from mangrove stands)						
Measured in the field						
Median grain size (µm)	29	5.1	11.6	6.5	144.8	25.7
Soil water content (%)	29	26.8	57.2	59.4	66.0	7.9
Wet bulk density (g cm^{-3})	29	1.2	1.4	1.4	1.7	0.1
Shear Strength (Pa)	29	0.3	1.5	1.0	4.0	1.2
Time submerged per day (%)	29	0.0	49.6	34.2	100.0	40.0
Slope (m m^{-1}), incl. as factor:	29	-0.1	0.03	0.00	0.2	0.1
negative	8	-0.083			-0.003	
low	7	-0.003			0.003	
moderate	7	0.003			0.056	
steep	7	0.056			0.178	
Derived from GIS						
Maximum shelter width (m)	29	0	284.3	141.4	735.4	288.7
Sand bank width (m)	29	0	40.0	0	134.4	50.7
Water fetch at low tide (m)	29	77.8	1143.5	2000	2000	908.6
Shelter by mudflat (m)	29	0	125.1	56.6	537.4	176.3

* celine.van.bijsterveldt@nioz.nl

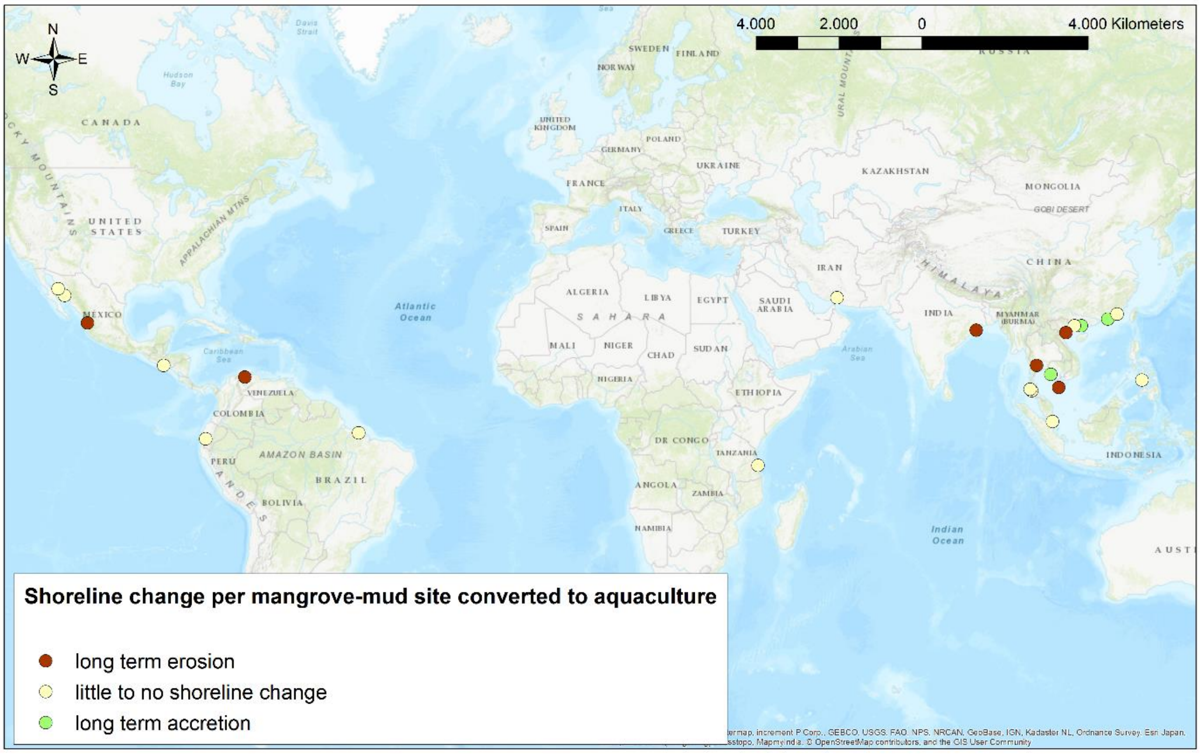

Figure 1 Long term shore line changes from 1984 until 2016 as reported by Luijendijk et al. (2018) averaged per aquaculture coast. Aquaculture coasts displayed are sites designated by RAMSAR as internationally important wetlands, distinguished by mangroves and mudflats that have been (partly) converted to aquaculture (RAMSAR, 2018).

* celine.van.bijsterveldt@nioz.nl

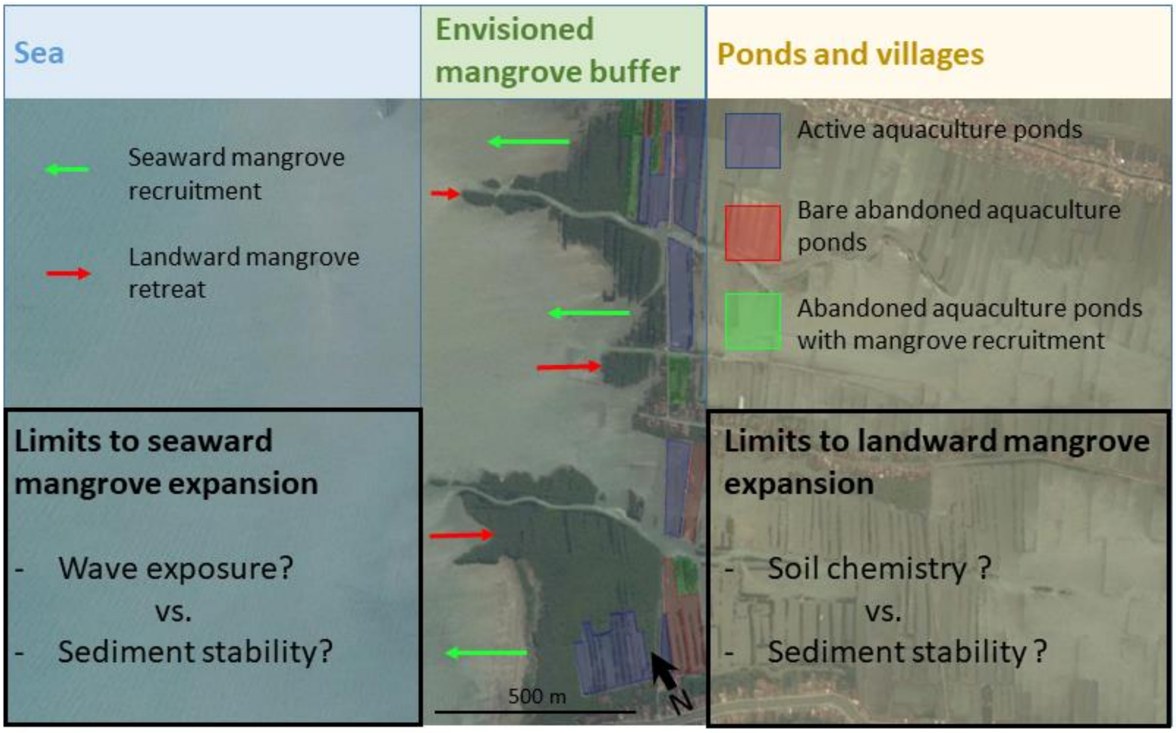

Figure 2 Envisioned mangrove greenbelt buffer along the eroding aquaculture coastline of Demak, Java, Indonesia. Natural expansion of existing mangrove stands in seaward direction is occurring with varying success, possibly due to wave exposure or sediment instability. Natural mangrove expansion of existing mangrove stands landwards into abandoned aquaculture ponds also occurs with varying success, possibly related to unfavourable soil chemistry due to poor drainage or sediment instability. The role of these variables in landward and seaward mangrove expansion is investigated here.

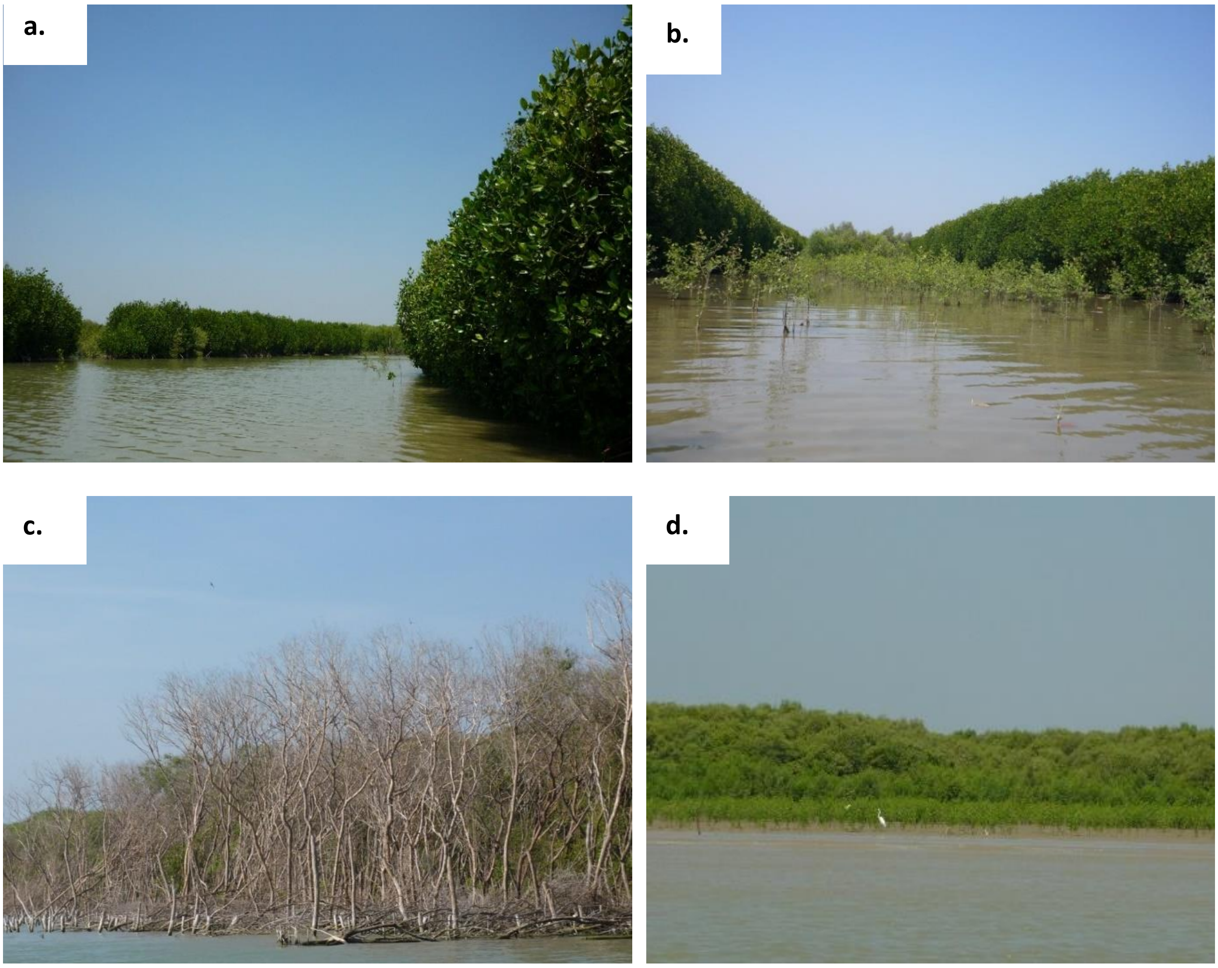

Figure 3 Examples of mangrove retreat and recruitment in Demak (photos by Celine E. J. van Bijsterveldt). a. Abandoned aquaculture pond with little recruitment. b. Sheltered pond land inward of a mangrove stand with *Avicennia marina* recruitment inside the pond and planted *Rhizophora mucronata* trees outlining the old pond bunds. c. Mangrove retreat at the sea side of a mangrove stand. d. Mangrove recruitment seaward of a mangrove stand. Three subsequent stages of mangrove recruitment are visible.

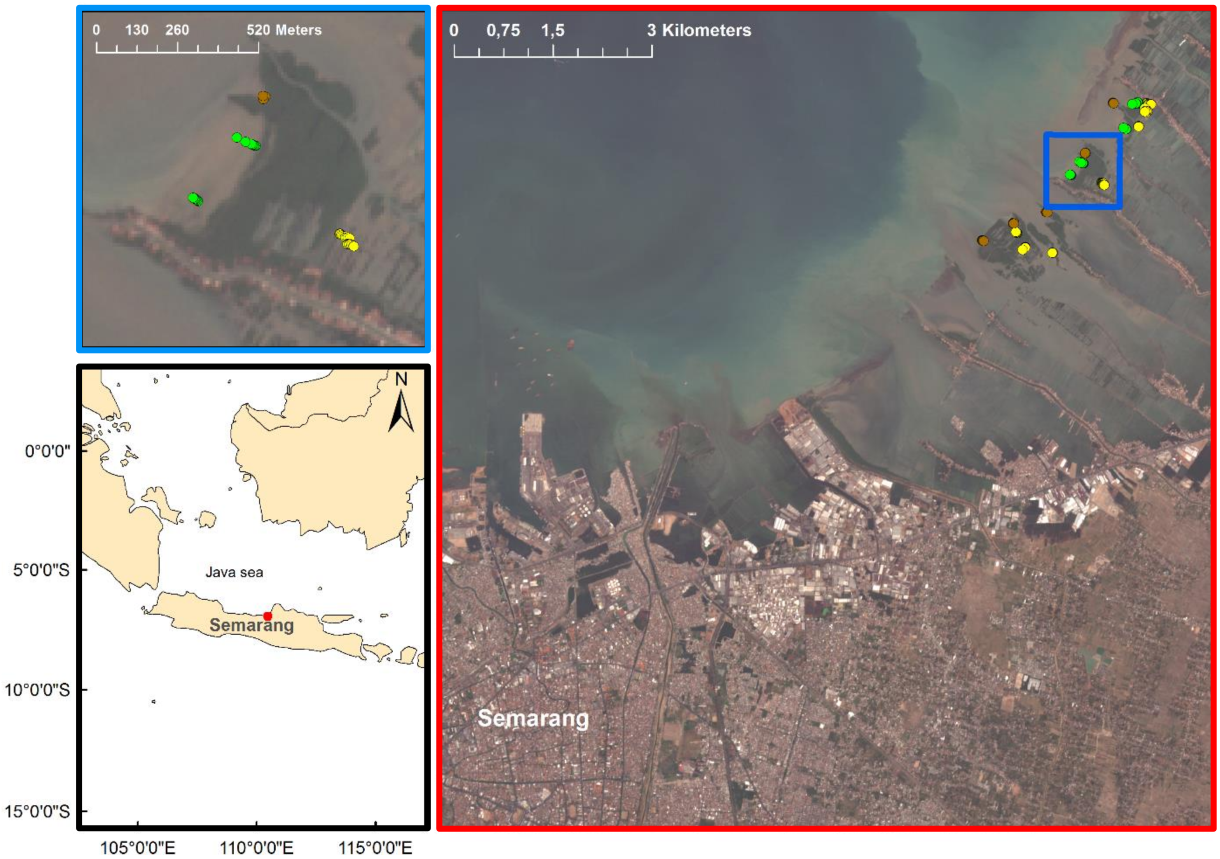

Figure 4 . Location of the study area Demak (red box) obtained from a Copernicus Sentinel-2 MSI satellite image and its orientation on Java, Indonesia (black box). Yellow points represent stations in abandoned aquaculture ponds, green points represent stations along expanding mangrove transects, and brown points represent stations at mangrove retreat sites. Blue box: a close-up of three abandoned aquaculture pond transects (yellow points represent stations), two expanding mangroves stand transects (green stations) and one mangrove retreat stand transect (brown stations).

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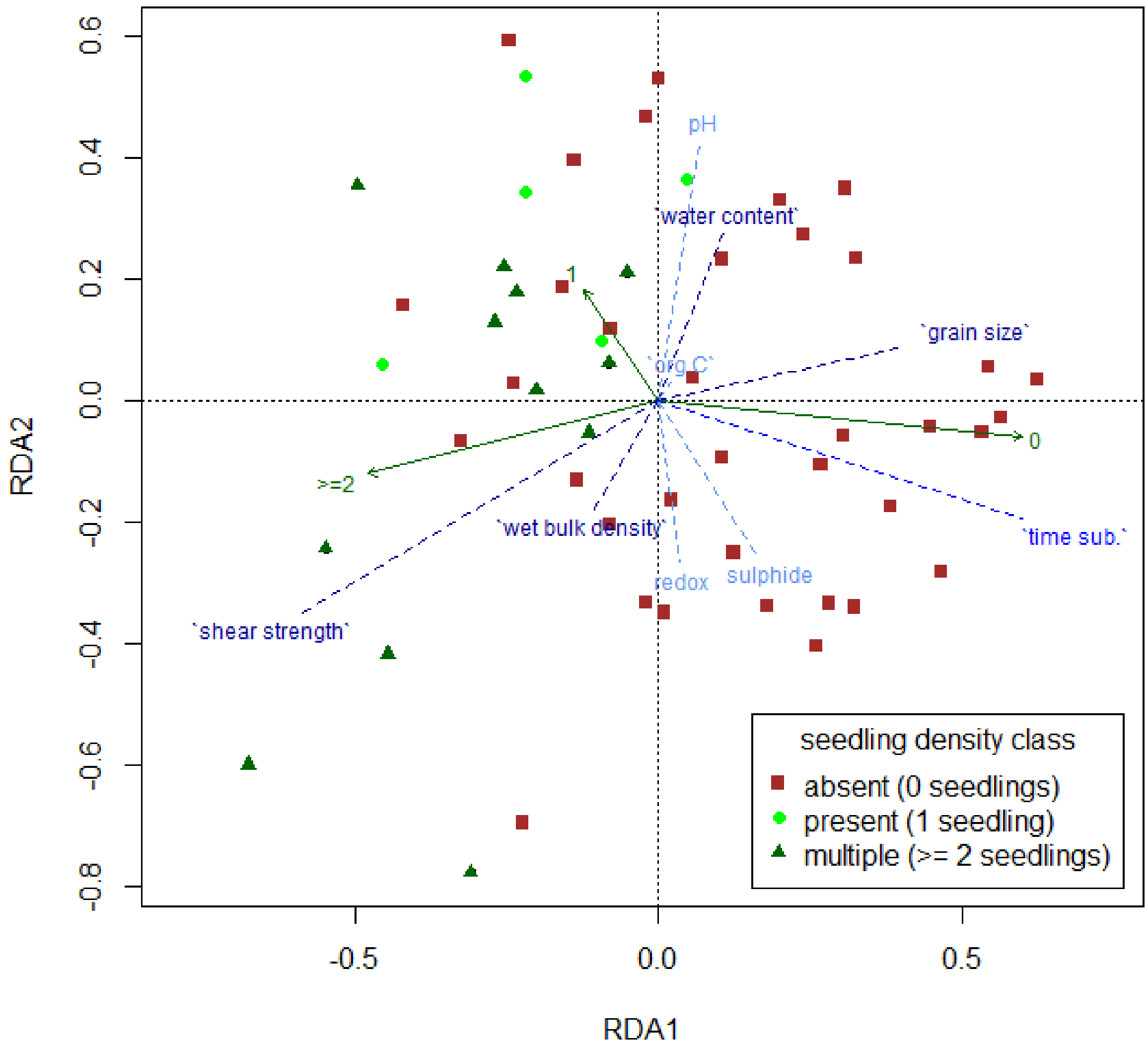


Figure 5 Statistical analysis of parameters controlling mangrove establishment in abandoned aquaculture ponds. The RDA correlation plot relates three seedling density classes (i.e., absent, present, multiple) to the environmental parameters. Our analysis covered 53 stations spread out over 11 abandoned aquaculture ponds. Stations are plotted according to their similarity in number of seedlings, and coloured according to the number of seedlings observed (see legend). The correlation between stations in terms of seedling density is displayed with green solid vectors. The relation between seedling density and every explanatory variable can be interpreted by the direction of the dashed vector of interest to the response category vector. Vectors in the same direction are positively correlated, vectors in the opposite direction are negatively correlated and

perpendicular vectors are not correlated. E.g., the shear strength arrow roughly points in the same direction as the arrow for stations with multiple seedlings, indicating that high shear strength often coincides with high seedling density. Environmental parameters that we investigated are depicted as dashed vectors and coloured by group: submergence time (% per day) in blue; soil stability parameters shear strength (*Pa*), median grainsize (*μm*), soil bulk density ($g\ cm^{-3}$) and soil water content (*%*) in dark blue; and soil chemistry related parameters soil acidity (pH), sulphide concentration in pore water (*μM*), redox potential (- *mV*) and soil organic carbon content (*%*) in light blue. Only environmental parameters along the horizontal RDA axis explain the variation in seedling density significantly, i.e. 14% (R^2 adj. RDA1= 14%, $p < 0.05$ and R^2 adj. RDA2 =1%, p = 1).

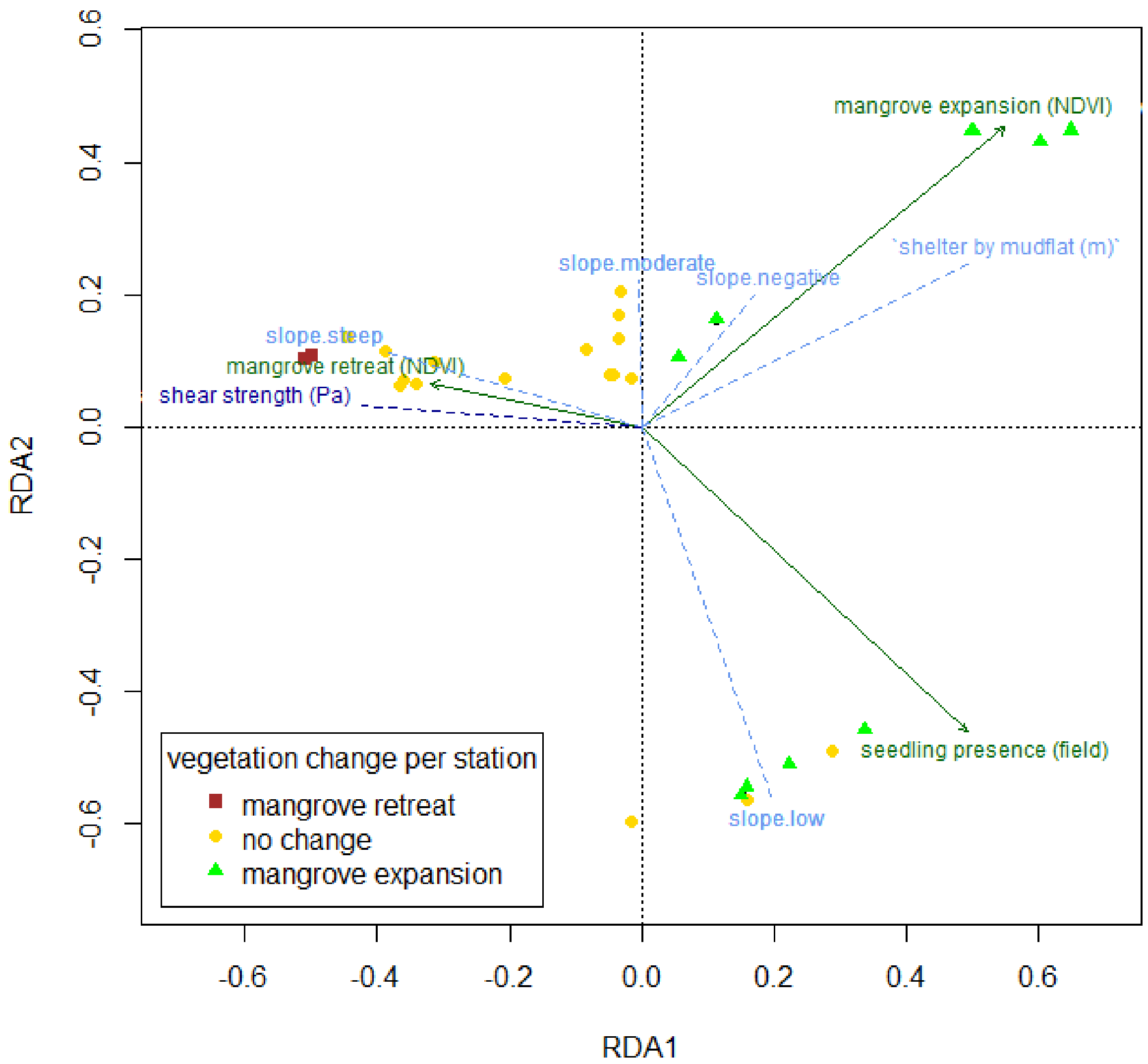


Figure 6 Statistical analysis of parameters that drive seaward mangrove expansion. The RDA correlation plot shows the 29 stations that were investigated, coloured according to the condition as observed in the field and with GIS: seedling presence or mangrove expansion (green dots), stations that did not change state over the wet season (yellow dots) and stations that showed mangrove retreat (brown dots). We related three seaside mangrove conditions (1: mature mangrove retreat landward based on NDVI change over the wet season of 2015-2016, 2: mature mangrove expansion seaward based on positive NDVI change over the same wet-season and 3: seedling presence in the field) with environmental parameters related to soil stability and wave exposure. The relation between the three seaside mangrove conditions (green, solid arrows) and

the environmental parameters related to wave exposure (light blue dashed arrow) and soil stability (dark blue dashed arrow) can be deduced from the direction of the arrows similarly as in Figure 5. In general, all environmental parameters that work along the horizontal axis explain 17 % of the variance in seaside mangrove dynamics ($p < 0.01$) and along the vertical axis explain 11 % ($p < 0.05$) of the variance.

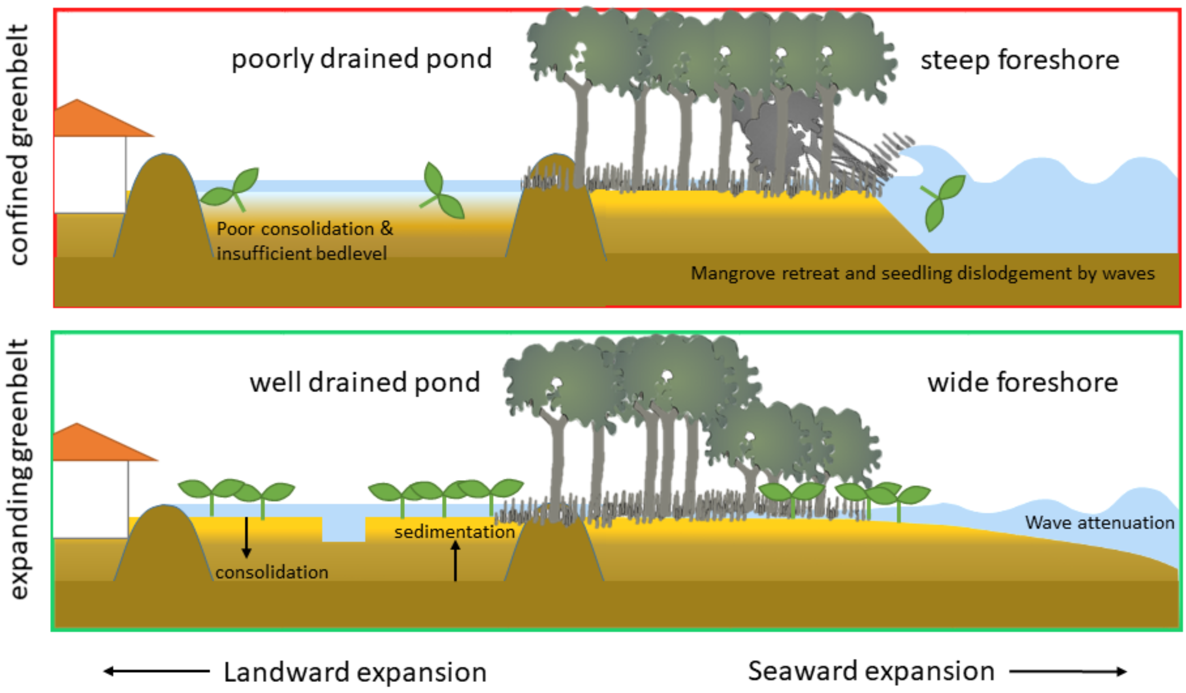
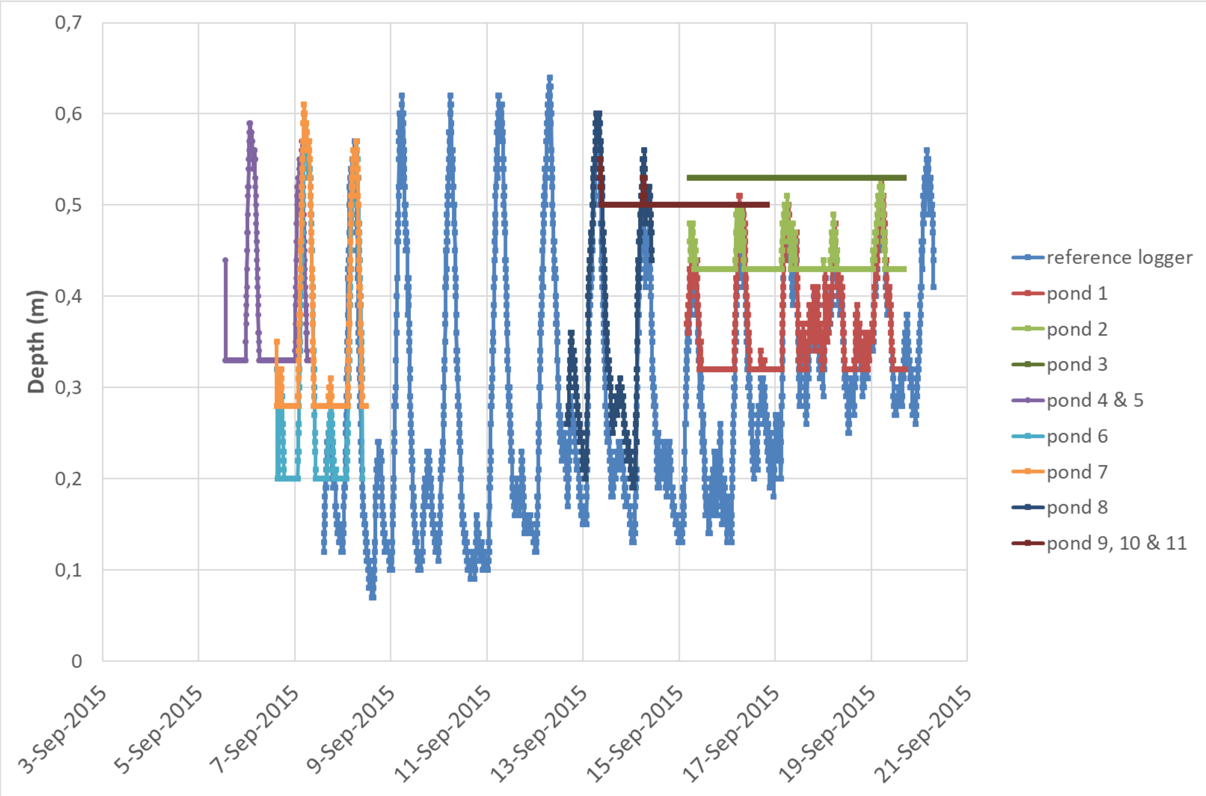


Figure 7 Conceptual figure showing factors that negatively (red box) and positively (green box) influence mangrove greenbelt expansion. Landward expansion: poorly drained aquaculture ponds may have insufficient sedimentation to reach a good surface elevation (red box), or contain poorly consolidated sediment too unstable for seedling anchorage (red box). Conversely, ponds with improved hydrological connectivity would have better sediment consolidation due to improved drainage and more sediment input resulting in accretion (green box). Seaward expansion: existing mangroves are at risk for collapse when there is a deep foreshore with a steep profile (red box) and are more likely to expand seaward when there is a foreshore with a gentle slope like a mudflat (green box).

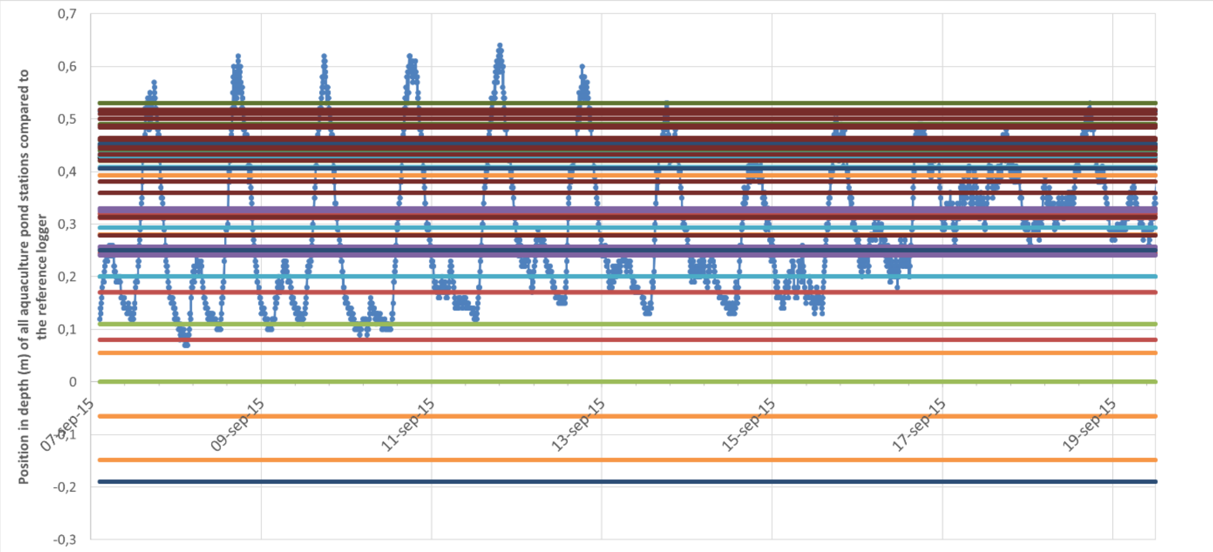
9 Appendix A. Supplementary data

Data in support of this article can be found online at https://doi.org/10.4121/uuid:522c81ad-e989-4374-8ac9-10367c6d4b23

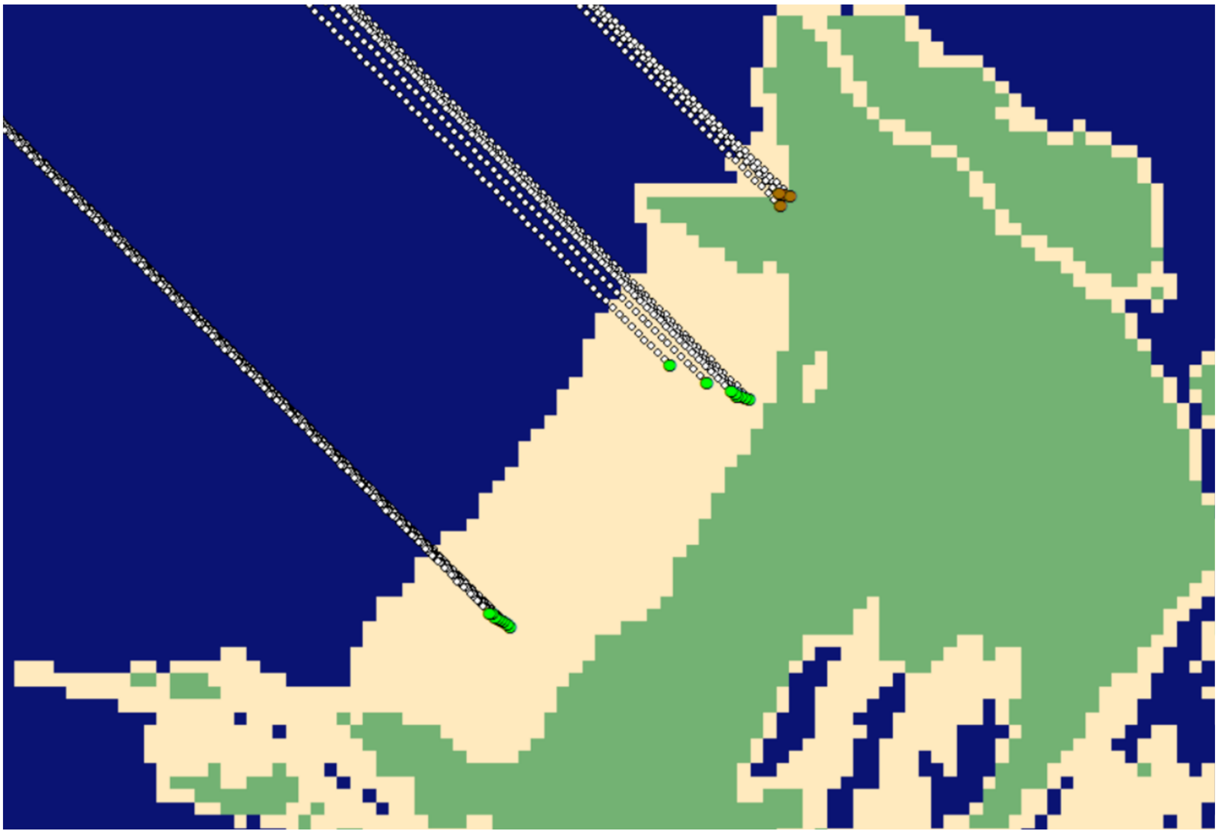
10 Appendices



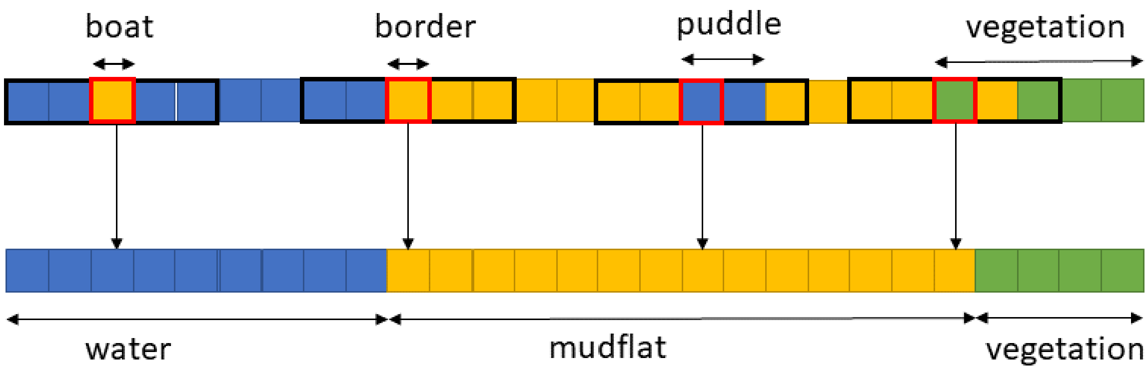
A1 Tidal inundation measured with pressure sensors at 11 aquaculture ponds compared to a subtidal reference station in open water (reference logger). Aquaculture ponds with ID number 4 and 5 and ponds 9, 10 and 11 had the same water level logger.



A2 Calculated position in the intertidal of every measurement station (coloured lines) relative to the tidal range of the subtidal reference station (blue dots). Station lines are coloured per pond, corresponding to the pond colours of A1.



A3 Example detail of classified raster image based on Sentinel 2 NDVI data, with vegetation (green), exposed sediment (yellow) and water (blue) (see main text for classification). Bearing lines (white dots) are indicated for all field-stations along two field transects with mangrove expansion as observed in the field (seedling recruitment on the mudflat) as green dots, and one transect with mangrove retreat as observed in the field (mature mangrove retreat) as brown dots.



A4 Smoothening process of mudflat and water bodies in cells of bearing lines to exclude false positives in the raster classification such as boats on the water and puddles on a mudflat. Classification of single and double cells are transformed to the value found in the majority of a group of five cells: the cell of interest and two neighbouring cells in both directions.