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Original Article

Roles of aboveground roots facilitating sedimentation and elevation change in a mangrove forest behind bamboo seawalls

Saijai Samosorn[1], Tanuwong Sangtiean[2], Chadtip Rodtassana[1], and Sasitorn Poungparn[1*]

[1] *Department of Botany, Faculty of Science, Chulalongkorn University, Pathum Wan, Bangkok, 10330 Thailand*

[2] *Department of Marine and Coastal Resource, Ministry of Natural Resource and Environment, Lak Si, Bangkok, 10210 Thailand*

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Abstract

We studied sedimentation rates and elevation changes in a naturally rehabilitated-mangrove forest dominated by *Avicennia* spp. and compared the results to a seedling plantation of *Rhizophora mucronata* and a bare soil area behind bamboo seawalls in Samutsakorn, Thailand. The average sedimentation rates in the forest plots (0.0196 g cm^{-2} d^{-1}) were significantly lower than those in the bare-soil plots (0.0269 g cm^{-2} d^{-1}) which had a greater variation in the sedimentation rates that indicated a less consistent sedimentation rate on the exposed soil surface. Consequently, the annual net elevation changes were positive in the plots with the presence of mangrove roots (ranging from 6.37-10.87 cm) compared to negative changes in the bare-soil plots (ranging from –5.97 to –12.97 cm). The results highlighted the importance of the natural mangrove forest having a higher potential to accumulate sediments and stabilize the coastal area compared to the adjacent bare soils area behind the bamboo seawall.

Keywords: aboveground root, mangrove forest, sedimentation rate, elevation change, bamboo seawall

1. Introduction

Mangrove forests are one of the important vegetation types that cover the coastal areas in tropical regions. They have the unique characteristic of a large amount of plant biomass allocated to their root systems (Komiyama *et al*., 2000; Ong, Gong, & Wong, 2004). The high proportion of root biomass in mangroves is not only advantageous for carbon accumulation (Komiyama *et al*., 2000; Patil, Singh, Naik, Seema, & Sawant, 2012), but the complex structure of mangrove roots also causes a high intensity of sedimentation (Furukawa & Wolanski, 1996; Furukawa, Wolanski, & Mueller, 1997) and functions as a land builder (Kathiresan, 2003). The sedimentation processes in mangrove forests are related to the aboveground root systems, whereby the plant roots reduce the current speed and increase the turbulence of the water (Mazda & Ikeda, 2006; Mazda & Wolanski, 2009). Therefore, the retention time of the sediment suspension imported into the mangrove forests is prolonged and consequently promotes the sedimentation process (Furukawa & Wolanski, 1996; Krauss, Allen, & Cahoon, 2003; Van Santen, Augustinus, Janssen-Stelder, Quartel, & Tri, 2007).

The aboveground root system and the sedimentation process in mangrove forests have been studied mainly in terms of the relationship between the rate of sedimentation and the root density (Bird, 1986; Spenceley, 1977; Young & Harvey, 1996) or root diameter (Krauss *et al*., 2003). The presence of mangrove trees and aboveground roots block the water flowing through a mangrove forest. They resist the water flow by the drag force and by the eddy viscosity due to water turbulence between their gaps (Furukawa & Wolanski,

*Corresponding author
Email address: sasitorn.p@chula.ac.th

1996). A model of hydrodynamics in a mangrove swamp was proposed by incorporating the aboveground root structure including root height, surface area, and volume (Mazda & Wolanski, 2009). These parameters may reduce water velocity and promote sedimentation in mangrove forests depending on micro-topography and structure of vegetation.

Here, the relationships between aboveground root structures and the sedimentation characteristics (sedimentation rate and net elevation change) were observed in a naturally rehabilitated-mangrove forest located behind bamboo sea-walls which were constructed to protect the coastal erosion. These characteristics were compared to an adjacent area of a sapling plantation and a bare soil area without vegetation.

2. Materials and Methods

2.1 Study site

The study site was located on the east coast of the Tha Chin river mouth (13°29′ N, 100°20′ E) facing the Gulf of Thailand in Samutsakorn Province in central Thailand. It is managed by the Centre for Marine and Coastal Conservation No. 2 of the Department of Marine and Coastal Resources, Thailand. This coastal area was classified as having a moderate degree of erosion by the Department of Marine and Coastal Resources, Thailand. In 2006, four-layered bamboo walls were constructed parallel to the coastline in front of a mangrove forest to prevent coastal erosion. Each layered wall is 0.3–0.9 m in width and ≥26 m in length (Figure 1). A plantation of *Rhizophora mucronata* seedlings was established within the inner layer of the bamboo seawalls (line 3 and 4, Figure 1) with the bamboo poles that were randomly arranged in the plantation at a height of about 1.0 m. The bare soil area is located between the outermost layers of the bamboo seawalls (line 1 and 2, Figure 1). The study area is subject to a mixed semidiurnal dominated tide, according to the Royal Thai Navy, Thailand, and is also influenced by the northeast monsoon from November to February and the southwest monsoon from May to October. The daily tide usually moves from the sea in a north-south direction (Figure 1).

A natural stand of mangrove forest dominated by *Avicennia alba* Blume, and *A. marina* (Forssk.) Vierh., has developed here since 2009. Three plots of sizes 9×8, 5.5×9, and 5.5×9 m were studied in this forest (F1–F3, Figure 1). In addition, we established two study plots of sizes 8×21 m and 18×21 m in a 2-year old sapling plantation of *R. mucronata* (P1 and P2) and three study plots each of 5×25 m in an area of bare soil without any vegetation (S1–S3) that were adjacent to the natural forest plots (Figure 1). Relative elevations of the substrate ranged between –10 to 40 cm in the forest plots, while the plantation and bare soil plots had relative elevations of –20 to 10 cm and –30 to 20 cm, respectively.

Inundation periods (h d^{-1}) of each plot were calculated using the relative elevation of the substrate and predicted heights of water above the lowest low water by the Royal Thai Navy from May 2012 to April 2013. According to the relative elevation of the substrate, the inundation periods were recorded from the longest to the shortest in the bare soil plots > the forest plots > the plantation plots at 16±2 > 12±2 > 9±2 h d^{-1}, respectively.

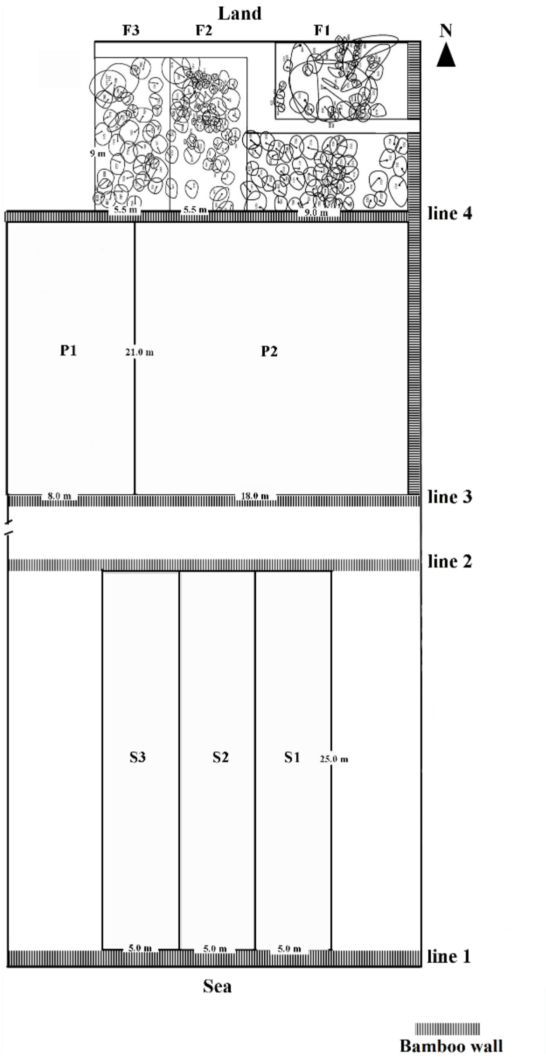

Figure 1. The study area was comprised of three *Avicenna* sp. mangrove forest plots (F1–F3), two *R. mucronata* plantation plots (P1 and P2) and three bare soil plots (S1–S3) which were all located behind a different layer of the bamboo seawall.

2.2 Structure of the aboveground root system

All of the trees with the stem diameter at breast height (DBH) of >1.0 cm in the F1–F3 plots were identified to species level and counted. The number of *R. mucronata* seedlings in the P1 and P2 plots were counted and used to calculate the seedling density. Fifteen subplots, each of 25×25 cm in size, were established within each plot and all of the aboveground roots (i.e. pneumatophores of ≥4.0 cm height and prop roots) were counted and their diameter at the ground level and height above the ground level were recorded. Aboveground root density was then calculated in the unit of root m^{-2}. The root surface area (cm^2 m^{-2}), cross-sectional area (cm^2 m^{-2}), and volume (cm^3 m^{-2}) of the pneumatophores and prop roots were calculated assuming the roots were conical and cylindrical in shape, respectively. The measurements were performed every two months from May 2012 to March 2013.

2.3 Sedimentation rates

The rates of sedimentation were measured monthly from May 2012 to April 2013 using the filter trap method (Marion, Anthony, & Trentesaux, 2009). Each filter trap consisted of an acrylic cylinder (11.2 cm diameter and 1.0 cm height) with a PVC ring and a filter sheet. The filter sheet was filter paper (Whatman No. 5) inserted between two layers of fibreglass mesh. Five filter traps were placed in each study plot at ground level during a low tide and each trap was attached to a bamboo pole to fix the trap at the same location during the entire length of the experiment. Every 6–10 d the filter papers were collected to obtain the dry weight, which were later oven-dried at 60 °C to a constant dry-weight, and replaced with a fresh one. The weights of the filter papers before and after installation in the trap were deemed to be the dry weight of the deposited sediment, and the sedimentation rate was calculated as g cm^{-2} d^{-1}.

2.4 Changes in ground elevation (sedimentation/erosion)

The net level of sedimentation or erosion of the ground surface was measured bimonthly from May 2012 to April 2013 in terms of the changing elevation using stainless steel pins (Krauss *et al*., 2003). The stainless steel pins (1.0 cm diameter and 100 cm height) were installed at 70 cm soil depth at the four corners and at the center of each 1×1 m subplot which resulted in five pins per plot. Three 1×1 m subplots were established in each study plot (F1–F3, P1, P2, and S1–S3). The lengths of the stainless steel pins were measured every two months using a meter ruler (scale 0.1 cm) from the exposed length of the pin to the level of soil surface. The lengths of the pins above the soil surface represented the elevation change. A positive elevation change (i.e. a decrease in the length of the exposed pins over the 2-month period) indicated sediment accumulation, while negative values indicated erosion. Moreover, the net annual elevation change was calculated from the summation of the bimonthly elevation changes over the 1-year period.

2.5 Bulk density of soil

Three soil samples per plot were randomly taken using a stainless steel soil core (5.0 cm inside diameter and 13 cm height) in October 2012 and April 2013. The soil samples were oven-dried at 80 °C to a constant weight. Soil bulk density was calculated from a ratio of dry weight to its fresh volume.

2.6 Soil particle distribution

Soil particle distribution at three soil depths of 0–20 cm, 20–40 cm, and 40–60 cm was determined in August 2012 and April 2013 using the hydrometer method (Bouyoucos, 1927).

2.7 Data analysis

Annual budget of gross sediment over a 1-year period (kg m^{-2} y^{-1}) of each plot was obtained from the summation of the monthly budget of gross sediment which was calculated by the rate of sedimentation of a respective month multiplied by the number of days in that month. Net budget of sediment (kg m^{-2} y^{-1}) of each plot was calculated from the net elevation change over the 1-year study period (cm y^{-1}) multiplied by the soil bulk density (g cm^{-3}) of that plot.

The differences in sedimentation rate and net elevation in each plot were analysed by one-way analysis of variance (ANOVA), and followed by Tukey's test. The relationships between the aboveground root structure and process of accretion were analyzed using Pearson correlation. All analyses used the SPSS (version 17) software.

3. Results and Discussion

3.1 Forest structure

The mangrove forest at this study site was composed of five tree species, namely *Avicennia alba* Blume, *A. marina* (Forssk.) Vierh., *Rhizophora apiculata* Blume, *R. mucronata* Poir., and *Sonneratia caseolaris* (L.) Engl. In the forest plots (F1–F3), *A. alba* and *A. marina* were the co-dominate species with a tree density that shared 52.0% of the total. The average stem densities of the trees were 15,067 stem ha^{-1} in March 2012 and 13,059 stem ha^{-1} in March 2013 (Table 1). The average increment in the stem basal-area was 9.10 m^2 ha^{-1} during the 1-year period. The forest structure showed that *A. alba* and *A. marina*, which are pioneer species on the new mudflats, occupied and grew well on the muddy coast behind the bamboo seawalls. The growth of this mangrove forest, which was principally *Avicennia* sp., was determined from the tree biomass using a common allometric equation for the calculation (Komiyama, Kato, & Poungparn, 2005). In this study the average aboveground biomass (55.43–100.72 t ha^{-1}) was comparable to that reported for a secondary mangrove forest in southern Thailand with 90.25 t ha^{-1} in Satun Province (Komiyama *et al*., 2000) and 62.2 t ha^{-1} in Phang-nga Province (Poungparn, 2003). Root biomass obtained at this study site (29.91–52.45 t ha^{-1}) was comparable to the secondary mangrove forests in eastern Thailand at Trat Province with 39–57 t ha^{-1} (Poungparn *et al*., 2012). Therefore, the growth of the natural-rehabilitated *Avicennia* forest behind the bamboo seawalls was comparable to other secondary mangrove forests in Thailand. This implied that the protection from bamboo seawalls in this study site possibly assisted vegetation development on the eroded coastline.

3.2 Aboveground root systems

The root sizes including diameter, height, cross-sectional area, surface area, and volume of the pneumatophores and prop roots are summarized in Table 2. The large variation in each parameter was due to the growth of new roots and the death of existing roots during the study period.

Table 1. Parameters of *Avicennia* sp. (*Av*) and *Rhizophora* sp. (*Rh*) trees with a diameter at breast height of >4.5 cm and saplings from May 2012 to March 2013.

Plot	No. of *Av* trees	No. of *Rh* trees	No. of trees and saplings	% of trees	Density (stem ha^{-1})	Stem basal area (m^{2}ha^{-1})	Above-ground biomass (t ha^{-1})	Root biomass (t ha^{-1})
March 2012								
F1	9	0	129	7.0	18,333	15.59	65.13	34.51
F2	0	0	59	0.0	17,576	13.87	53.54	29.61
F3	10	0	46	21.7	9,293	11.58	47.63	25.61
Average					15,067	13.68	55.43	29.91
March 2013								
F1	32	5	107	34.6	15,139	27.79	125.19	64.25
F2	0	0	59	0.0	15,555	21.69	86.49	46.56
F3	18	0	42	42.9	8,484	18.86	90.48	46.53
Average					13,059	22.78	100.72	52.45

Table 2. Parameters of the pneumatophores and prop roots in five study plots: *Avicennia* sp. mangrove forest (F1–F3) and *R. mucronata* sapling plantation (P1 and P2) from May 2012 to March 2013.

Plot	Month	Pneumatophore						Prop root					
		D_0 (cm)	Height (cm)	Density (roots m^{-2})	Cross-sectional area (cm^{2}m^{-2})	Surface area (cm^{2}m^{-2})	Volume (cm^{3}m^{-2})	D_0 (cm)	Height (cm)	Density (roots m^{-2})	Cross-sectional area (cm^{2}m^{-2})	Surface area (cm^2 m^{-2})	Volume (cm^{3}m^{-2})
F1	May 12	0.60	14.8	548	153.34	7643.87	764.39	0.00	0.00	0.00	0.00	0	0.00
	Jul 12	0.61	14.6	565	163.12	7904.07	803.58	0.00	0.00	0.00	0.00	0	0.00
	Sep 12	0.69	14.7	621	230.86	9894.14	1137.83	0.00	0.00	0.00	0.00	0	0.00
	Nov 12	0.71	16.9	710	283.20	13382.07	1583.54	0.00	0.00	0.00	0.00	0	0.00
	Jan 13	0.61	17.0	739	215.90	12037.69	1223.83	0.00	0.00	0.00	0.00	0	0.00
	Mar 13	0.65	16.0	833	273.09	13608.12	1474.21	0.00	0.00	0.00	0.00	0	0.00
F2	May 12	0.62	12.9	306	91.75	3844.35	397.25	0.08	0.19	6.40	0.03	0.31	0.01
	Jul 12	0.66	12.0	322	111.90	4005.91	440.65	0.08	0.88	6.40	0.03	1.42	0.07
	Sep 12	0.65	12.4	324	108.38	4102.04	444.39	0.08	0.94	6.40	0.03	1.51	0.08
	Nov 12	0.58	14.7	372	97.62	4982.05	481.60	0.09	1.10	6.40	0.04	1.99	0.10
	Jan 13	0.61	13.6	371	107.28	4834.62	491.52	0.08	0.90	6.40	0.03	1.45	0.07
	Mar 13	0.62	13.4	345	102.82	4502.31	465.24	0.08	0.74	6.40	0.03	1.19	0.06
F3	May 12	0.59	19.1	211	57.52	3734.98	367.27	0.23	0.56	3.20	0.13	1.29	0.36
	Jul 12	0.62	16.9	251	75.11	4131.16	426.89	0.23	2.77	3.20	0.13	6.40	1.81
	Sep12	0.67	17.9	288	101.87	5425.51	605.85	0.22	2.81	3.20	0.12	6.21	1.78
	Nov 12	0.63	19.6	323	101.42	6264.97	657.82	0.23	2.67	3.20	0.13	6.17	1.70
	Jan 13	0.55	17.5	336	81.06	5079.96	465.66	0.20	2.74	3.20	0.10	5.51	1.42
	Mar 13	0.58	17.1	346	92.13	5390.39	521.07	0.24	2.66	3.20	0.14	6.42	1.93
P1	May 12	0.04	1.2	30	0.03	2.26	0.02	0.65	10.49	18.13	6.02	388.36	56.39
	Jul 12	0.09	1.2	36	0.25	6.11	0.09	0.62	12.58	18.13	5.47	444.24	60.27
	Sep12	0.10	2.2	54	0.45	18.66	0.31	0.88	18.69	18.13	11.03	936.78	181.55
	Nov 12	0.18	6.0	113	2.81	191.70	5.75	1.21	19.72	18.13	20.85	1359.06	362.06
	Jan 13	0.18	8.3	113	3.02	265.18	7.96	1.24	20.45	18.13	21.89	1444.32	393.31
	Mar 13	0.20	10.4	135	4.10	441.08	14.70	1.39	19.66	18.13	27.51	1556.49	480.43
P2	May 12	0.03	0.8	14	0.01	0.53	0.003	0.27	4.87	4.27	0.24	17.64	4.39
	Jul 12	0.03	0.9	15	0.01	0.64	0.003	0.03	5.00	4.27	0.003	2.01	5.62
	Sep 12	0.04	1.0	15	0.02	0.94	0.01	0.26	4.61	4.27	0.23	16.08	3.87
	Nov 12	0.07	3.7	45	0.19	18.31	0.21	0.32	3.09	4.27	0.34	13.26	3.99
	Jan 13	0.07	3.2	49	0.17	17.24	0.20	0.32	4.11	4.27	0.34	17.64	5.43
	Mar 13	0.09	3.8	67	0.40	35.99	0.54	0.34	3.73	4.27	0.39	17.01	5.48

The pneumatophore density in the mangrove forest and plantation plots tended to increase over the study period. The average pneumatophore density in the forest plots (F1–F3) ranged 211–833 roots m^{-2} (Table 2). This was higher than previously reported for a *S. alba* stand in Micronesia with 45–51 roots m^{-2} (Krauss *et al*., 2003). The lower pneumatophore density in Micronesia was possibly a result of relatively high cross-sectional area of the *S. alba* pneumatophores of 313–548 cm^2 m^{-2} (Krauss *et al*., 2003) compared to the *Avicennia* pneumatophores in this study (57.5–283.2 cm^2 m^{-2}). However, the root densities obtained in this study were in the range reported for an *A. marina* forest in Kenya of 200–2,500 roots m^{-2} (Dahdouh-Guebas, Kairo, Bondt, & Koedam, 2007). Therefore, the growth of pneumatophores in this forest was not different from the natural forests dominated by *Avicennia*.

3.3 Sedimentation rates and elevation changes

The average sedimentation rates over the study period ranged from the lowest in F1 plot (0.0130±0.0038 g

cm^{-2} d^{-1}) to the highest in S2 plot (0.0286±0.0124 g cm^{-2} d^{-1}) (Figure 2). The average sedimentation rates in the bare soil plots (S1–S3) were significantly higher than those in the forest and plantation plots (Figure 2). The high sedimentation rate in the outermost bare soils plots might be a result of daily tides and water movements which horizontally affected the sedimentation process in general (Kathiresan, 2003; Kumara, Jayatissa, Krauss, Phillips, & Huxham, 2010). The water movement in this study site was in a north-south direction, thus the flood tide carried a large amount of suspended sediment to the bare soil plots that were located in the outermost area close to the sea (Figure 1). Moreover, the relatively long period of inundation with a large volume of inundated water in the bare soil plots possibly prolonged the retention time for the suspended sediment to settle on the substrate. The low rates of sedimentation in the forest and plantation plots (F1–F3 and P1–P2) compared to the bare soil plots indicated that the higher tree density may cause less weight of sediment to settle on the forest floor. Mangrove trees and their aboveground roots, including prop roots and pneumatophores, blocked the water flow and increased the turbulence on the uneven mud floor (Mazda & Wolanski, 2009). Nevertheless, the sedimentation rates in the bare soil plots showed a higher degree of variation than those in the forest and plantation plots (Figure 2). This suggested that the sedimentation rate on the forest floor was more consistent than in the area of an exposed soil surface. Therefore, the high stem density and the close forest canopy, that reduced the impact of vertical raindrops and strong current, probably acted as a shelter to stabilize the sedimentation processes on the forest floor.

The average sedimentation rate for the three forest plots (F1–F3) was 0.0196 g cm^{-2} d^{-1}, which was much higher than reported for the interior mangrove forests at the Red River Delta in Vietnam (0.0070 g cm^{-2} d^{-1}) (Stelder, Augustinus, & Van Santen, 2002) and at Airai Bay in Micronesia (0.0076 g cm^{-2} d^{-1}) (Golbuu, Victor, Wolanski, & Richmond, 2003). However, the sedimentation rate at the inland mangrove forest in this study was lower than the rates at the edge of the mangrove forest along the Red River Delta in Vietnam (0.0225–0.0510 g cm^{-2} d^{-1}) (Stelder *et al*., 2002) and at Airai Bay in Micronesia (0.0295 g cm^{-2} d^{-1}) (Golbuu *et al*., 2003). Similarly, a study in southeast Queensland in Australia reported higher sedimentation rates in the fringe zone of a mangrove forest compared to the inland area (Adame, Neil, Wright, & Lovelock, 2010). The sedimentation rate was affected by the distance from the river to the forest. The suspended sediments were carried by the daily tides and the high rate of sedimentation was usually seen at the edge of the mangrove forest which was near the source of suspended sediment imported from the bay (Golbuu *et al*., 2003). Regardless of the plots, the sedimentation rates at the area along the coast behind the bamboo seawalls obtained by this study varied in a narrow range in comparison to those reported for a mangrove forest along the coast of Micronesia (0.0090–0.0650 g cm^{-2} d^{-1}) (Victor, Golbuu, Wolanski, & Richmond, 2004). Overall, the hard-structure seawalls constrained the movement of sediment (Gittman *et al*., 2016). The bamboo seawalls in this study possibly stabilized the rate of sedimentation in the area behind them and, in particular, assisted in the important role of sediment accumulation in the natural mangrove forest.

The soil elevation changes occurring in the coastal area was a result of long-term sedimentation (Wolanski, Mazda, & Ridd, 1992). At this study site, the bimonthly elevation changes (Figure 3) were always positive (0.2–2.8 cm) in the forest plots (F1–F3), mostly positive in the plantation plots (P1 and P2), and the highest magnitude of elevation changes was found in the bare soil plots (S1–S3) (–5.8 to 6.4 cm). The soil bulk density in the bare soil plots (0.483±0.034 g cm^{-3}) was lower than the average soil bulk density of the forest and plantation plots (0.503±0.034 g cm^{-3}), and the lowest soil bulk density was recorded in the plantation plots (0.435±0.061 g cm^{-3}). The proportions of clay particles in the bare soil, forest, and *R. mucronata* plantation plots averaged 31.31±7.9%, 38.37±8.8%, and 35.53±7.3%, respectively (Table 3). From August 2012 to April 2013, the clay particles in the bare soil plots increased only 0.76%. However, the clay particles of the forest plots increased 5.11%. Sato (2003) reported that the mangrove swamps trapped and accumulated more fine particles and sediment compared to the open coast. Moreover, less water movement in the well-sheltered areas favoured finer particle deposition (Gomes *et al*., 2016). In this study, both bamboo seawalls and vegetation structures possibly caused low water movement compared to the bare soil area.

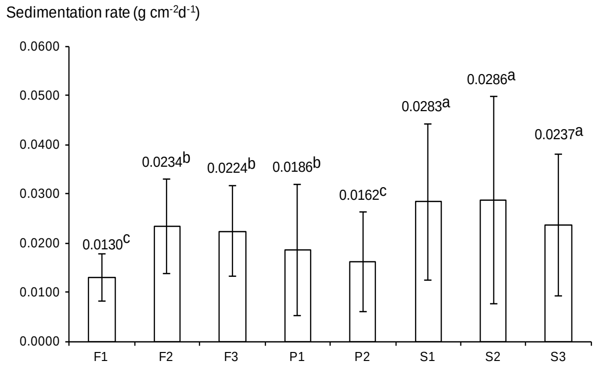

Figure 2. Average sedimentation rate in the *Avicenna* sp. mangrove forest (F1–F3), *R. mucronata* sapling plantation (P1and P2) and bare soil (S1–S3) study plots. Data are shown as the mean±1SD. Means with a different lower case letter are significantly different (P<0.05, Tukey's test).

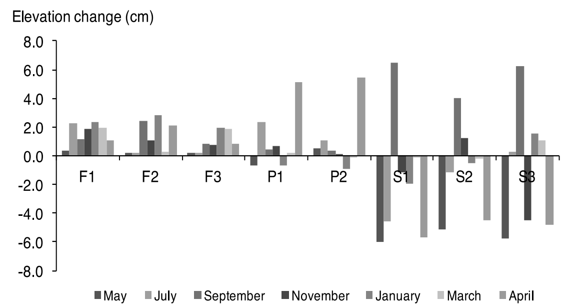

Figure 3. Bimonthly elevation changes from May 2012–April 2013 (inclusive) in the *Avicennia* sp. mangrove forest (F1–F3), *R. mucronata* sapling plantation (P1 and P2), and bare soil (S1–S3) study plots.

Table 3. Distribution of particle sizes and soil texture in the *Avicennia* sp. mangrove forest (F1–F3), *R. mucronata* sapling plantation (P1 and P2), and bare soil plots (S1–S3) in August 2012 and April 2013. S = silt, SC = silty clay, SL = silt loam, SCL = silty clay loam

Soil depth (cm)	August 2012				April 2013			
	% clay	% silt	% sand	texture	% clay	% silt	% sand	texture
F1–F3								
0–20	23.82	69.07	7.11	SL	35.77	61.26	2.97	SCL
20–40	35.37	59.63	5.00	S	45.49	54.28	0.23	SC
40–60	48.25	50.66	1.09	SC	41.51	57.72	0.76	SC
P1–P2								
0–20	33.93	59.56	6.51	SCL	22.10	66.66	11.25	SL
20–40	43.38	53.66	2.97	SCL	35.70	62.74	1.56	SCL
40–60	38.58	56.88	4.55	SCL	39.46	60.54	0.00	SCL
S1–S3								
0–20	21.61	66.37	12.02	SL	26.25	63.80	9.95	SL
20–40	34.43	62.57	3.00	SCL	26.16	69.46	4.37	SL
40–60	36.74	61.35	1.90	SCL	42.64	56.98	0.38	SC

The net elevation change over the 1-year study period was positive in the forest and plantation plots which ranged 6.37–10.87 cm (Figure 4), which showed an accretion of sediment deposition in the plots with the presence of aboveground roots. In contrast, the bimonthly elevation changes in the bare soil plots (S1–S3) varied in a wide range and most of the changes were negative (Figure 3) and the net elevation changes of S1–S3 were negative (Figure 4), which indicated erosion of the soil surface. Higher net elevation changes and the greater proportions of clay particles in the forest and plantation plots in this study implied that the mangrove forest facilitated the sedimentation processes, which, especially, stabilized the sediment fluxes even though the sedimentation rate was low. The forest canopy, which functioned as a shelter, decreased the turbulence from airflow downwind which allowed fine suspended particles to deposit on the forest floor (Wolanski, 2006). The high density of the aboveground roots resisted the water flow and consequently increased water turbulence between the gaps of the roots (Furukawa & Wolanski, 1996). The increased water turbulence kept fine particles suspended above the forest floor. Although there were higher sedimentation rates in the bare soil plots, the negative net elevation changes with the wider range of elevation changes over the 1-year period in these plots showed unstable sediment fluxes even with protection from the bamboo seawalls. The seawalls interfered with the waves and increased the up-drift accretion but also possibly caused down-drift erosion (Hedge, 2010).

We balanced a budget of sediment between the gross and net budget of sediment in the respective plot (Table 4). It was remarkable that only the F1 plot with the highest density of *Avicennia* trees showed a gain in sediment at the rate of 0.0198 kg m^{-2} d^{-1}, while the other plots had sediment loss that inferred soil erosion with the average rates of 0.3803 (S1–S3 plots), 0.0923 (P1–P2 plots), and 0.1208 kg m^{-2} d^{-1} (F2–F3 plots). The *R. mucronata* plantation plots (P1–P2) exhibited the lowest rates of erosion. The negative net elevation changes and rates of sediment loss over one year in the bare soil plots were caused by no barrier to reduce the current velocity (e.g., vegetation structure). Thus, the deposited sediment was easily washed away by the currents in the exposed soil plots. This highlights the ability of the mangrove root systems to stabilize soil elevation changes by maintaining consistent sedimentation and decreased erosion rates.

A significant correlation was found between the sedimentation rate and the elevation change (Pearson correlation, r=0.492, P=0.009, n=30; Table 5) in the forest plots and *R. mucronata* plantation plots. This positive correlation underlined the importance of mangroves in stabilizing the coastal area.

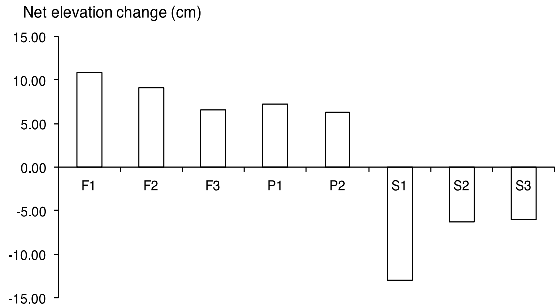

Figure 4. Net elevation change over the 1-year study period in the *Avicenna* sp. mangrove forest (F1–F3), *R. mucronata* sapling plantation (P1 and P2), and bare soil (S1–S3) study plots.

Table 4. Estimated gross, net, and balanced budget of sediment (kg m^{-2} y^{-1}) in the *Avicennia* sp. mangrove forest (F1–F3), *R. mucronata* sapling plantation (P1 and P2), and bare soil plots (S1–S3) from May 2012 to April 2013. Negative value of net budget of sediment means erosion of soil surface. (+) and (-) value of budget of sediment is respectively defined as loss and gain sediment over the 1-year study period.

Plot	Budget of sediment (kg m^{-2} y^{-1})		
	Gross	Net	Balance
F1	47.42	54.66	-7.24
F2	85.58	45.93	39.65
F3	81.84	33.34	48.50
P1	67.76	31.69	36.07
P2	59.02	27.73	31.30
S1	103.39	-62.72	166.10
S2	104.43	-30.65	135.08
S3	86.37	-28.88	115.26

Table 5. Pearson correlation between the structures of aboveground root and the processes of accretion in five study plots of the *Avicennia* sp. mangrove forest (F1–F3) and *R. mucronata* sapling plantation (P1 and P2).

Variable	r	P-value
Sedimentation rate with:		
Height of pneumatophore	0.395	0.042
Elevation change	0.492	0.009
Elevation change with:		
Density of pneumatophore	0.540	0.004
Density of aboveground root	0.542	0.004
Volume of pneumatophore	0.534	0.002
Cross-sectional area of pneumatophore	0.539	0.002
Cross-sectional area of aboveground root	0.530	0.003
Surface area of pneumatophore	0.550	0.002

Note: Data were from 30 replicates.

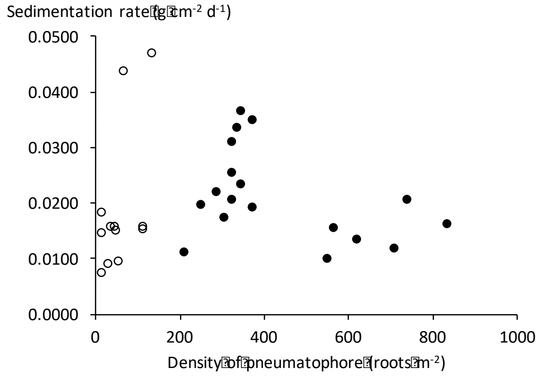

Figure 5. Relationship between the sedimentation rate and pneumatophore density in the forest plots (closed circle, n=18) and plantation plots (opened circle, n=12).

3.4 Relationships between aboveground roots and sedimentation characteristics

The relationship between the aboveground root structures and the accretion processes in the study plots are summarized in Table 5. The sedimentation rate was significantly correlated to the pneumatophore height, where higher pneumatophores may function as a barrier to tidal currents and facilitate sedimentation. Nevertheless, there was no significant correlation between the sedimentation rate and pneumatophore density (Figure 5) either in the forest plots (Pearson correlation, P=0.102, n=18) or in the plantation plots (Pearson correlation, P=0.071, n=12). The non-significant correlation in the plantation plots was likely due to great variations in the sedimentation rates. However, the very high densities of pneumatophores (>372 roots m^{-2}) in the forest plots resulted in a non-significant correlation between the pneumatophore density and the sedimentation rate (Figure 5). Regardless of the plots, the sedimentation rate tended to increase with the increased pneumatophore density up to a density of 372 roots m^{-2}. A significant correlation (r=0.423, P=0.039, n=24) was found when the pneumatophore density ranged from 0 to 372 roots m^{-2} (Figure 5). A similar trend was also reported previously by Young & Harvey (1996), where a positive correlation between the sediment accretion and the density of artificial pneumatophores was found when the pneumatophore density was lower than 350 roots m^{-2}. However, in a separate study, there was no correlation between the sediment accretion and density of artificial pneumatophores (Spenceley, 1977), but soil surface erosion occurred at a high density of 10,000 roots m^{-2}. High pneumatophore density might promote sedimentation by increasing the friction between the root surface and tidal current by retaining the suspended sediment for a longer time in the mangrove forests which facilitated the sedimentation process (Furukawa & Wolanski, 1996). However, a very high pneumatophore density tended to create erosion rather than sedimentation due to the higher degree of water turbulence around the pneumatophore surface (Mazda & Wolanski, 2009). Consequently, the suspended sediment could not settle to the bottom which resulted in lower rates of sedimentation or even erosion.

In this study, the elevation change was significantly and positively correlated with density, volume, and cross-sectional and surface areas of the pneumatophores (Table 5), which inferred the advantages of the aboveground root systems to promote the elevation increment. This agreed with a previous study which reported that the density of artificial pneumatophores was positively correlated to sedimentation causing the elevation change (Young & Harvey, 1996).

4. Conclusions

In conclusion, our study showed that the mangrove forest, including the plantation, behind the bamboo seawalls enhanced the sedimentation process and stabilized sediment fluxes in the coastal areas where the erosion usually occurred. The narrow range of sedimentation rates in this study compared to other studies in secondary mangrove forests suggested that the bamboo seawalls possibly assisted the mangrove forest in the sedimentation process at this study site. The positive correlations between the sedimentation rate and elevation change in the forest and plantation plots were elucidated. The elevation change also showed a positive correlation with the aboveground root structures, which implied that the aboveground roots may function as a barrier to the tidal current and create water turbulence between root surface and tidal flow. As a result, the suspended sediment is retained longer in the mangrove forest that facilitated sedimentation process. During the 1-year study, this mangrove forest showed a net accretion of sediment which contrasted with the net erosion in the bare soil area. Therefore, the mangrove forests behind the bamboo seawall are important in coastal stabilization via the sedimentation process. However, the results from this study are site-specific which did not allow us to draw a conclusion. Further studies are suggested in order to conclude that the mangrove forests behind seawalls enhance coastal stabilization and sedimentation.

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