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Effect of high sedimentation rates on surface sediment dynamics and mangrove growth in the Porong River, Indonesia

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ABSTRACT

Large quantities of mud from the LUSI (Lumpur Sidoarjo) volcano in northeastern Java have been channeled to the sea causing high rates of sediment delivery to the mouth of the Porong River, which has a cover of natural and planted mangroves. This study investigated how the high rates of sediment delivery affected vertical accretion, surface elevation change and the growth of *Avicennia sp.*, the dominant mangrove species in the region. During our observations in 2010–2011 (4–5 years after the initial volcanic eruption), very high rates of sedimentation in the forests at the mouth of the river gave rise to high vertical accretion of over 10 cm y^{-1}. The high sedimentation rates not only resulted in reduced growth of *Avicennia* sp. mangrove trees at the two study sites at the Porong River mouth, but also gave rise to high soil surface elevation gains.

1. Introduction

Mangroves are intertidal plant communities that are widespread on tropical accreting shorelines and establish when sediments accumulate at elevations close to mean sea level. Their extensive above and below-ground root systems trap and stabilize sediments, thus influencing rates of sedimentation, which may differ along environmental gradients (Furukawa and Wolanski, 1996). As a result of mangrove-facilitated accretion, gradual elevation of the sediment surface in relation to sea level can occur, indicating their capacity to maintain their elevation with respect to rising sea levels (Saenger, 2002; Cahoon and Guntenspergen, 2010). Surface elevation change can be dependent to sediment availability (Lovelock et al., 2015), which are influenced by a range of factors including rainfall (including amount and intensity), river catchment characteristics (e.g. topography and soil characteristics), human activities (e.g. dredging, watershed deforestation and agricultural practices), and catastrophic events (intense tropical storms and floods) (Thrush et al., 2004; Cahoon, 2006).

Change in sediment regimes in coastal regions can have detrimental effects on nearby estuaries and their coastal habitats (Thrush et al., 2004), including mangroves which are sensitive to natural and anthropogenic environmental changes (Ellison and Farnsworth, 1996; Cahoon, 2006, Souza Filho et al., 2006, Gilman et al., 2008), in particular sediment regime changes (Terrados et al., 1997; Ellison, 1998; Thampanya et al., 2002). While mangroves thrive on accreting shorelines, excess sediment input can cause negative impacts on mangroves, including reduced seedling establishment, altered plant physiology, reduced tree growth, lower macrobenthic diversity and tree mortality (Jimenez et al., 1985; Terrados et al., 1997; Ellison, 1998; Thampanya et al., 2002; Ellis et al., 2004). Mangrove seedling survival and growth has been observed to decline with low oxygen in the root zone (McKee, 1996) and with increasing sediment accretion (Terrados et al., 1997; Thampanya et al., 2002). Sediment burial of the aerial roots of adult mangroves and lenticels in young mangroves limits diffusion of air into the root system and failure of the plant to continue to provide aeration for the roots causes reduced growth and mortality (Ellison, 1998; Saenger, 2002). Additionally, plants allocate more biomass to roots when growing under anoxic conditions which reduces above-ground growth (McKee, 1996; Saenger, 2002; Krauss et al., 2014). Conversely, in situations where there is erosion and sediments do not accumulate, plants must adjust their root systems in order to remain anchored and survive. In such situations the extensive shallow cable root systems of several mangrove species, for example those in the genus *Avicennia*, may effectively anchor the plants (Saenger, 2002).

In the Porong River in East Java, the eruption in 2006 and subsequent management of a mud volcano named Lumpur Sidoarjo (LUSI) has

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resulted in markedly elevated sediment concentrations and sediment delivery to the coast (Mazzini et al., 2007, Soegiarto et al., 2012). The aim of this study was to determine the significance of the elevated sediment loading for mangrove growth. We examined how high fluvial sediment loads at the mouth of the Porong River in East Java contributed to surface elevation change and how these short-term high sedimentation rates affect the growth of the dominant mangrove species, *Avicennia sp.*, at the mouth of the Porong River. Our hypothesis was that the growth rate of trees would be reduced by high rates of vertical accretion. To this end, we undertook time series measurements of sediment deposition, surface elevation change and tree growth in the mangrove forests. We assessed the relationship between sedimentation rates, surface elevation gain and tree growth over the study period.

2. Materials and methods

2.1. Site description

The study site is located 20 km east-southeast of Sidoarjo in the northern part of East Java, Indonesia (7° 33′ 56″ S, 112° 52′ 14″ E) (Fig. 1). It has a tropical climate dominated by the monsoon, with average annual rainfall of 2200 mm (Jennerjahn et al., 2004). The Porong River is the southernmost distributary channel in the delta of the Brantas River. The Brantas River catchment has an area of 11,800 km^2, which comprises approximately 25% of the East Java Province, with mountainous, forested headwaters partly cleared for agricultural production, several large dams (Sengguruh, Sutami, Lahor, Wlingi, Lodoyo, Selorejo, Bening and Wonorejo) and coastal lowlands dominated by rice cultivation and aquaculture that have a dense network of irrigation canals and associated infrastructure. At Mojokerto, approximately 48 km upstream from the Porong River mouth, the Brantas diverges into two main distributary channels, the Surabaya River, which flows north to the coast at the city of Surabaya, and the Porong River, which flows to the east. A complex of control structures manipulates flows between the Surabaya and Porong Rivers in order to ensure domestic and industrial water supply to the city in the dry season and to reduce the flood hazard in Surabaya city in the wet season when almost 80% of the Brantas River flow is through the Porong River to the Madura Strait (Jennerjahn et al., 2004).

The Brantas River delivers high sediment loads and generates a prograding delta (Milliman and Syvitski, 1992, Tanaka and Ishida, 1999, Jennerjahn et al., 2004), which has prograded at a rate of about $0.4 \times 10^6\ m^2\ y^{-1}$ over the period 1935 to 1981 (Hoekstra, 1987). During the dry season, the Porong River discharge is low due to both low rainfall and the diversion of river flow to Surabaya city for domestic and industrial water supply (Jennerjahn et al., 2004, Soegiarto et al., 2012). Wet season flows in the Porong River are high due to the combined effects of Brantas River flow diversion to the Porong River and higher rainfall (Jennerjahn et al., 2004, Soegiarto et al., 2012). In addition to increased stream sediment loads arising from catchment land use, very high sediment loads have occurred in the Porong River due to the catastrophic eruption of the LUSI mud volcano in Sidoarjo, East Java. The eruption occurred on 29 May 2006 (Cyranoski, 2007; Mazzini et al., 2007) about 30 km downstream of Mojokerto and 1.9 km north of the Porong River (Fig. 1). Eruption of the mud occurred at an initial rate of 120,000 $m^3\ d^{-1}$ (Mazzini et al., 2007), and had declined to 50,000 $m^3\ d^{-1}$ by September 2011 (Soegiarto et al., 2012). Sediment released from the LUSI mud volcano is predominantly clay (81.5%) with porosity of approximately 30% and dry bulk density ranging between 1.24–1.37 g cm^{-3} (Soegiarto et al., 2012) in contrast to the sandy bedload that previously dominated sediment transport in the Porong (Hoekstra and Tiktanata, 1988). The erupted mud resulted in the destruction of villages, infrastructure and livelihoods and caused local subsidence of the land surface (Cyranoski, 2007; Normile, 2007; Abidin et al., 2009). Since 2007, the volcanic mud has been disposed of by pumping to the Porong River in order to reduce the continuing damage to communities and infrastructure. The mud is subsequently entrained and transported to the coast by fluvial and tidal processes, resulting in concern for the viability of mangrove wetlands at the river mouth (Soegiarto et al., 2012). Large quantities of LUSI mud are pumped from the eruption sites to the Porong River through a network of pipelines and has increased the annual sediment loads of the Porong River by

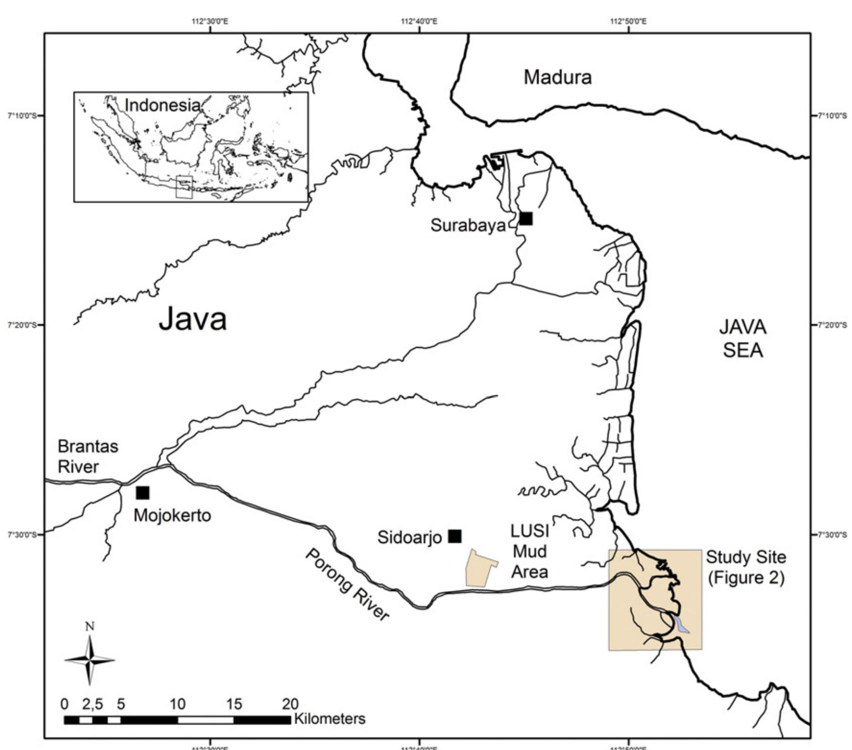

Fig. 1. Brantas River delta in East Java, Indonesia, showing the study site and the area affected by the LUSI mud volcano.

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three to four compared to pre LUSI values (Soegiarto et al., 2012, Jennerjahn et al., 2013).

2.2. Experimental design

Our study was conducted at the mouth of the Porong River (Fig. 2), approximately 19 km downstream from the mud eruption. The coastal system is tide-dominated with semi diurnal tides with a range of approximately 2.5 m (Jennerjahn et al., 2004). Sediment discharge is mainly transported southward from the river mouth into the Madura Strait (Priyono et al., 2008). Since LUSI mud discharge commenced, dredging has been undertaken to maintain navigable waterways and the dredge spoil used to construct an artificial island for created wetlands at the river mouth. The coastal ecosystems of the Porong River mouth include 550 ha of mangrove forests (MMAF, 2009) that have been degraded due to illegal logging, conversion to aquaculture ponds, pollution and high sedimentation (Davie and Sumardja, 1997; MMAF, 2006).

For this study, we selected two mangrove forests adjacent to the main outlet channel of the Porong River, one on the northern side and one on the southern side (Fig. 2). Both sites are adjacent to the main outlet channel of the Porong where LUSI mud enters the sea and sediment deposition was expected to be high. Mangrove forests had low diversity, dominated by *Avicennia*, with small trees (<4 m high) growing at high density. The combined effect of conversion of mangroves to aquaculture ponds since the 1950's and the high sedimentation and shoreline accretion rates occurring prior to the mud volcano eruption has resulted in local extinction of four mangrove species and dominance by *Avicennia sp. and Sonneratia sp.*, species commonly associated with accreting shorelines in the region (Davie and Sumardja, 1997).

The experiment commenced in May 2010 (week 1) and concluded in May 2011 (week 53). We defined the period November–May as the "wet season" and the period June–October as the "dry season" as indicated by the monthly river discharge of the Porong River (Fig. 3). River discharge during the study period varied from 61.27 $m^3\ s^{-1}$ (August 2010) to 428.77 $m^3\ s^{-1}$ (December 2010) and monthly pumped mud inputs varied from 284,412 m^3 (May 2010) to 2,289,344 m^3 (March 2011) (Fig. 3) with a total volume of 17,540,707 m^3 pumped to the river over the study period (Badan Penanggulangan Lumpur Sidoarjo (BPLS) data). Annual rainfall at Sidoarjo (Juanda Airport Station; Indonesian Bureau of Meteorology, Climatology and Geophysics (BMKG) data) was 2894.8 mm in 2010 and 1789.1 mm in 2011 with a total rainfall of 2510.6 mm over the study period. The experiment was terminated in May 2011 due to damage to the surface elevation monitoring instruments and the loss of one of the forests, which was cleared by local villagers.

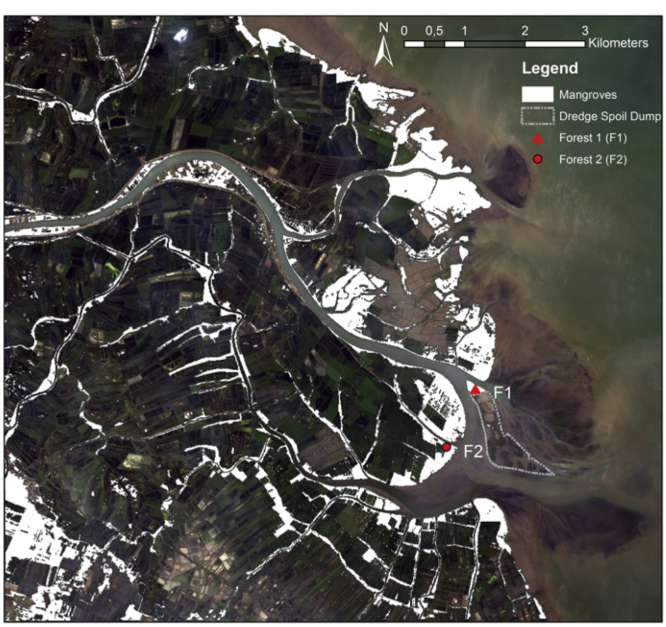

Fig. 2. Mangrove distribution at the Porong River mouth. The two monitoring sites (Forest 1 and Forest 2) and the dredge spoil island (dashed line) are shown (Advanced Land Observing Satellite (ALOS) imagery; September 2010).

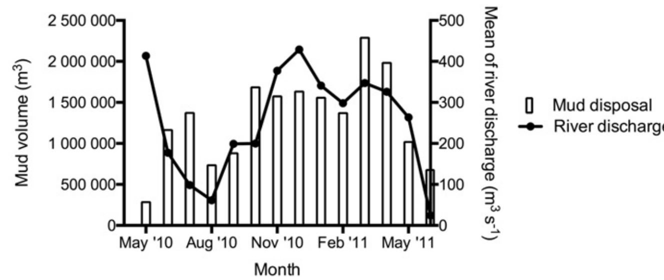

Fig. 3. Porong River discharge and monthly volcanic mud disposal during the observation period (May 2010–May 2011).
Data from Soegiarto et al. (2012).

2.3. Surface elevation change and vertical accretion

For the purposes of this study, we used techniques and terms adapted from Cahoon et al. (1995). Vertical accretion is the net effect of deposition (+) and erosion (−) of sediment at the observation site. Shallow subsidence is the net effect of root growth (+) and sediment settling and compaction (−). Thus, in principle, surface elevation change is equal to vertical accretion minus shallow subsidence. In practice, vertical accretion and surface elevation change are the measured parameters and shallow subsidence is calculated as: Shallow subsidence = Vertical accretion − Surface elevation change. Vertical accretion is the parameter of greatest relevance to mangrove growth response to changes in sedimentation rates. Surface elevation change, the change in elevation relative to a subsurface datum (Cahoon et al., 1995) is the parameter of greatest relevance to mangrove ecosystem response to sea level rise (Cahoon and Guntenspergen, 2010; Krauss et al., 2014).

Vertical accretion and surface elevation change were measured at three sites in each forest, with installation of the measuring equipment in April 2010 and measurements commencing in May 2010 and were repeated at interval of one to three months until May 2011. Vertical accretion at site was measured using sediment erosion pins. Five 60 cm long erosion pins per plot were inserted to 30 cm and accretion was measured from the soil surface to the top of the pin at each measurement interval. The difference between initial height and the measured height reflected the vertical accretion in the measurement period. This technique replaced the marker horizon of Cahoon et al. (1995), which was not feasible in Porong because of the high sedimentation rates. Surface elevation change was measured using the rod surface elevation table (RSET, Supplementary Fig. 1). Three RSETs were installed in each forest, which were installed to a depth of 12 m for all benchmarks.

2.4. Mangrove growth

Forest structure measurements were made in February 2010. Expandable dendrometer bands were set in February 2010 and the tree growth assessment commenced in July 2010. The growth of *Avicennia sp.* was calculated as the mean increment in basal area of randomly selected trees. The diameter increments of main stems were measured at approximately 1 m height on the main stem of 27 *Avicennia sp.* trees (13 in Forest 1 and 14 in Forest 2) using metal dendrometer bands (Krauss et al., 2007) and the change in cross sectional area (basal area) calculated for each measurement interval. Over the course of the experiment

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bands were lost, such that, by the final census, replication was reduced to five trees in Forest 1 and three trees in Forest 2 (Table 1).

2.5. Sediment characteristics

Five sediment samples were collected at each RSET station in natural forests and the dredge spoil island in February 2010, and the LUSI mud volcano site in April 2010, using a 35 ml syringe to take a 20 ml sample of surface soil. After drying in a 60 °C oven for 6 days, samples were weighed and the dry bulk density calculated. The samples were ground to a fine powder and subsampled for analysis of the percentage weight of carbon (C) and nitrogen (N) using a LECO TruSpec CHN analyzer at the University of Queensland, Australia. During transport to the laboratory all samples were treated with gamma radiation, a requirement of the Australian quarantine process. For stable isotope analysis of C and N, dried sediment samples were ground to a fine powder and analyzed using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20–20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK) at the University of California Davis Biogeochemistry Laboratory (Davis, USA). Samples for ^{13}C analysis were treated with 10% HCl to remove any carbonates and then re-dried in a 60 °C oven for 2 days prior to analysis. The relative contribution of potential sources (mangrove tissues and LUSI mud) to sedimentary organic matter pool at the study sites was examined using a simple two-source mixing model (Fry, 2006) and the value of $\delta^{13}C$ and $\delta^{15}N$ mangrove leaf litter from Kon et al. (2009).

2.6. Statistical analyses

Variations in vertical accretion and surface elevation change over the study period were assessed using two-way ANOVA, where season (wet or dry) was the fixed effect in the model and forests a random effect. The relationships between vertical accretion and surface elevation change, and between tree growth and vertical accretion was assessed using regression analyses. Differences among the sediment characteristics of the forests, the LUSI mud and the mud island sediments were assessed using two-way ANOVA. For tree growth rate analysis, a *t*-test was used to compare the complete observed dataset, which included replicates that were missing values later in the experiment (referred to the missing group), with the dataset that included only the replicates that remained until the last census (referred as the remaining group). This approach assessed the effect of missing values in the tree growth data. All analyses were conducted using the statistical package R (version 2.15.3 GUI 1.53) and Graphpad Prism 6.

3. Results

Vertical accretion in the Porong River mangrove forests was very high (Fig. 4). Over the observation period, with mean rates (±SE, N = 3) of vertical accretion were 14.9 ± 2.9 cm y^{-1} (Forest 1) and 16.3 ± 3.0 cm y^{-1} (Forest 2). The maximum vertical accretion measured was for the period November 2010 to January 2011 at Forest 2 when mean

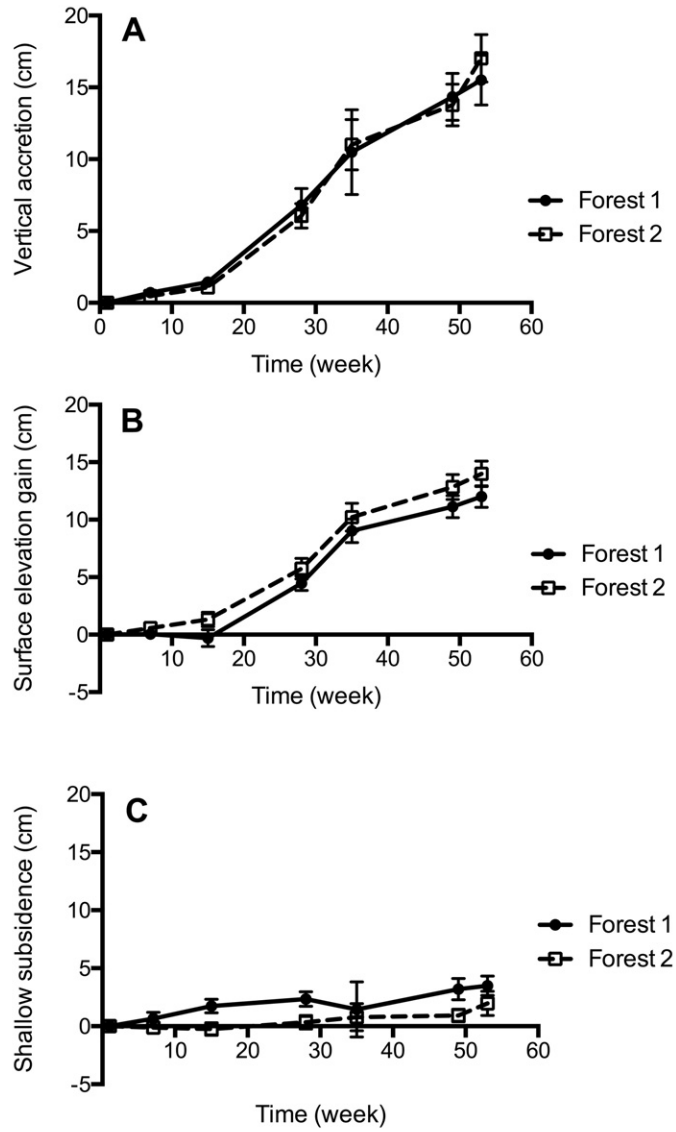

Fig. 4. Cumulative vertical accretion (A), surface elevation gain (B) and shallow subsidence (C) over the observation period (53 weeks) in the two mangrove forests in the Porong River mouth. Values are the means and standard error (N = 3) for each mangrove forest at each observation period.

of accretion occurred at an annualised rate of 37.0 cm y^{-1}. Mean rates of surface elevation change were 11.7 ± 3.0 cm y^{-1} (Forest 1) and 14.3 ± 2.3 cm y^{-1} (Forest 2).

Vertical accretion varied significantly with season (Table 2; P < 0.001) with mean rates (±SE, N = 3) of 19.6 ± 3.7 cm y^{-1} (Forest 1) and 20.5 ± 3.7 cm y^{-1} (Forest 2) in the wet season and 5.5 ±

Table 1
Growth rates of mangroves over the period of observation; mean, standard error and N for each mangrove forest for each observation period. P value and t show degree of difference in means of growth rates between the missing group (N = 13, N = 14) and remaining group (N = 5, N = 3). The reduction of replication for growth rates occurred over time due to loss of dendrometer band.

Period	Tree growth rates (cm^2 y^{-1})					
	Forest 1			Forest 2		
	N = 13	N = 5	P value (t)	N = 14	N = 3	P value (t)
July–September 2010	31.9 ± 4.8	17.0 ± 1.8	0.010 (2.93)	57.7 ± 5.5	57.2 ± 18.9	0.982 (0.03)
September–November 2010	16.9 ± 2.4	14.8 ± 1.7	0.483 (0.72)	17.1 ± 3.2	20.2 ± 13.5	0.846 (−0.22)
November 2010–January 2011	18.1 ± 4.5	11.9 ± 3.6	0.383 (0.91)	7.3 ± 1.5	8.4 ± 5.9	0.871 (−0.18)
January–April 2011	9.3 ± 2.8	9.3 ± 4.5	1 (0)	−7.4 ± 2.8	−9.4 ± 9.0	0.859 (0.19)
April–May 2011	6.8 ± 9.6	6.8 ± 9.6	1 (0)	3.1 ± 5.5	3.1 ± 5.5	1 (0)

Table 2
Summary of the characteristics of the sites and mangrove forests. The data include wet and dry season rainfall; river discharge and mud inputs in the Porong River; vertical accretion, surface elevation change and shallow subsidence of soils; and basal area increments of mangrove trees in the mangrove forests at the Porong River mouth (rainfall data from Juanda Airport Station; Indonesian Bureau of Meteorology, Climatology and Geophysics (BMKG); river discharge and mud input data from Badan Penanggulangan Lumpur Sidoarjo (BPLS)).

	Wet season (November–May)		Dry season (June–October)	
Monthly rainfall (mm)	140.8–398.5		15.5–269.2	
Monthly mean river discharge ($m^3\ s^{-1}$)	298.1–428.8		98.5–413.5	
Monthly mud inputs (m^3)	1,369,721–2,289,344		284,412–1,684,595	
	Forest 1	Forest 2	Forest 1	Forest 2
Vertical accretion ($cm\ y^{-1}$)	19.6 ± 3.7	20.5 ± 3.7	5.5 ± 1.2	4.0 ± 1.2
Surface elevation change ($cm\ y^{-1}$)	18.1 ± 3.0	18.9 ± 2.4	−0.9 ± 1.9	4.9 ± 1.6
Shallow subsidence ($cm\ y^{-1}$)	1.5 ± 4.0	1.6 ± 2.4	6.4 ± 2.2	−0.9 ± 1.6
Mangrove growth ($cm^2\ y^{-1}$)	14.2 ± 1.9	10.9 ± 1.5	31.9 ± 3.4	57.7 ± 4.6

1.2 $cm\ y^{-1}$ (Forest 1) and 4.0 ± 1.2 $cm\ y^{-1}$ (Forest 2) in the dry season. Nevertheless, despite the wet season exceeding dry season vertical accretion rates by a factor of about 4–5, the dry season rates were still high by comparison with reported values for mangrove sites elsewhere (e.g. Ellison, 1998).

Rates of surface elevation change also varied between seasons (Table 2, $P < 0.0001$), with surface elevation increasing over time at a mean rate (±SE, N = 3) of 18.1 ± 3.0 $cm\ y^{-1}$ (Forest 1) and 18.9 ± 2.4 $cm\ y^{-1}$ (Forest 2) in the wet season and −0.9 ± 1.9 $cm\ y^{-1}$ (Forest 1) and 4.9 ± 1.6 $cm\ y^{-1}$ (Forest 2) in the dry season. Mean rates of surface elevation change were correlated with rates of vertical accretion measured with the sediment erosion pins with a slope of 0.62 (Fig. 5, $F_{1,34} = 25$. $R^2 = 0.43$; $P < 0.0001$).

River discharge explained 50% of the variance in vertical accretion in the mangrove forests, with high vertical accretion associated with high discharge (Fig. 6, $R^2 = 0.50$; $P < 0.01$). LUSI mud disposal rates were not a significant determinant of vertical accretion rates in the mangroves ($R^2 = 0.13$; $P = 0.25$), although the availability of large quantities of pumped LUSI mud for fluvial and tidal transport to the mangrove forests

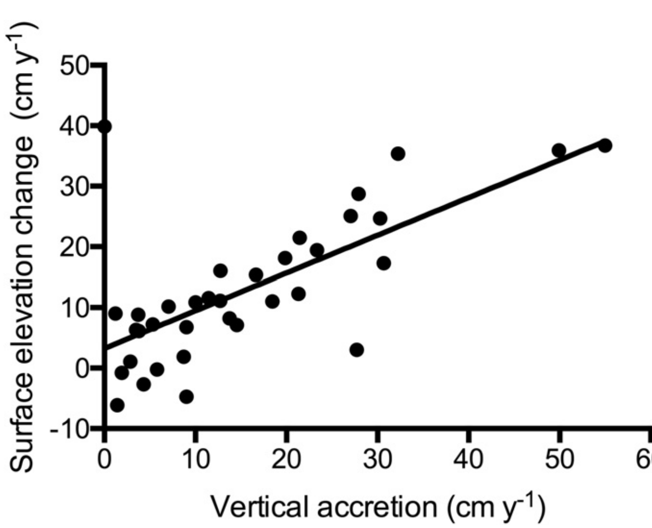

Fig. 5. The relationship between rates of vertical accretion ($cm\ y^{-1}$) and surface elevation change ($cm\ y^{-1}$). The form of the equation is: Y = 3.3 + 0.62 × vertical accretion rates, $R^2 = 0.43$, $P < 0.0001$. Values are means (N = 3) for 6 RSET stations at each site per observation period.

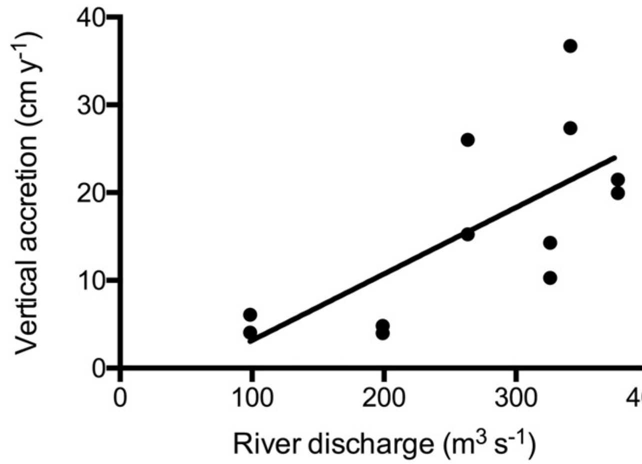

Fig. 6. Relationships between vertical accretion and river discharge. The line of best fit has the form: vertical accretion = −4.42 + 0.0758 × river discharge ($R^2 = 0.50$, $P < 0.01$). Values are the vertical accretion rates for each mangrove forest at each observation period.

underpins the very high vertical accretion rates observed in both wet and dry seasons (Table 2).

Shallow subsidence (calculated as accretion-elevation) occurred in the mangrove forest soils over the period of observation. Forest 1 tended to subside at greater rate (3.2 ± 2.9 $cm\ y^{-1}$) than Forest 2 (2.1 ± 1.2 $cm\ y^{-1}$) (Fig. 4, $F_{1,31} = 0.09$; $P = 0.76$), although Forest 1 subsided at a lower rate in the wet season (Table 2). Surface elevation decreased during the dry season in Forest 1 as a result of greater shallow subsidence than vertical accretion at this site in the dry season.

The basal area of the banded trees of *Avicennia sp.* ranged from 12.2 to 42.1 cm^2 (Forest 1) and from 11.8 to 51.0 cm^2 (Forest 2) with a mean height of 291 cm in Forest 1 and 279 cm in Forest 2. Mangrove trees grew at a mean rate of 19.9 ± 1.7 $cm^2\ y^{-1}$ and 30.2 ± 3.2 $cm^2\ y^{-1}$ in Forest 1 and Forest 2, respectively. Despite the reduction in replication over time, data were found to be robust because the means of tree growth in the missing group and in the remaining group were not significantly different (Table 1). Significant differences ($P < 0.0001$) in the growth rates were observed between wet and dry seasons, but not between sites ($P = 0.30$). Tree growth was slower during the wet season at both sites (Table 2, $P < 0.0001$). Overall, growth rates were lower during periods of high rates of vertical accretion of sediments (Fig. 7, $R^2 = 0.22$, $P < 0.0001$).

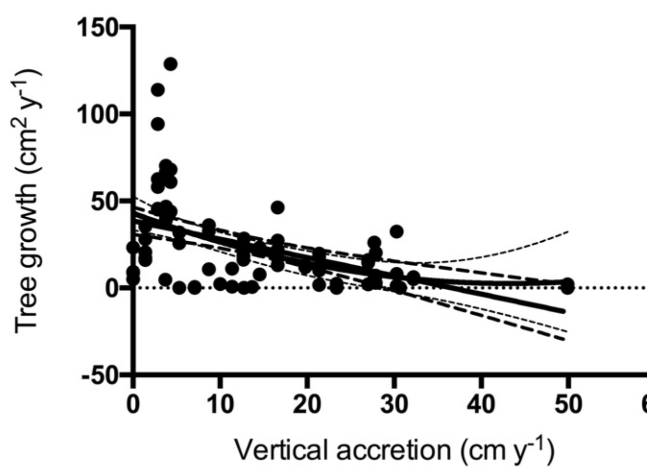

Fig. 7. Relationship between tree growth (basal area increment) and vertical accretion of sediments. The line of best fit has the form: tree growth rate = 38.6–1.05 × vertical accretion (linear; $R^2 = 0.22$, $P < 0.0001$); tree growth rate = 42.98–1.87 × vertical accretion + 0.02 × vertical accretion^2 (2nd order polynomial (dashed line); $R^2 = 0.26$; $P < 0.001$). Values are the growth rate for individual *Avicennia* trees.

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Table 3 summarizes variation of bulk density, sediment carbon content and isotopic composition of sediments in the forests, dredge spoil from the constructed island and LUSI mud. The three sediment types varied significantly in their dry bulk density ($F_{3,70} = 70.66$, $P < 0.0001$) and total carbon in sediment ($F_{3,31} = 12.56$, $P < 0.0001$) with higher dry bulk density and lower carbon content in LUSI mud. The $\delta^{13}C$ values also differed significantly among the sites ($F_{3,40} = 17.33$, $P < 0.0001$) with those in the forests were more negative than the values in both dredge spoil island and LUSI mud sediments. The ratio of $\delta^{13}C$ of LUSI mud to mangrove leaf litter in the sediments (LUSI mud: mangroves) was relatively high (0.57–0.81), indicating that a higher proportion of LUSI mud carbon than of mangrove litter derived carbon was present in mangrove soils at both sites, but also indicating that mangroves have contributed large quantities of organic carbon to the sediments as they are deposited.

4. Discussion

4.1. Sedimentation effects on vertical accretion and surface elevation dynamics of mangrove forest

Since 1962, large scale flood control, irrigation and water management programs have been implemented in the Brantas River Basin (Adi et al., 2013). Construction of large dams in the upper Brantas catchment, water extraction for irrigation and diversion structures which artificially increase Porong flows in the wet season and decrease them in the dry season, have markedly altered the hydrology of the Porong River. Erosion and sediment yield in the Brantas/Porong system have also been altered with high rates of soil loss from steep agricultural lands in the upper catchment, sediment trapping in reservoirs and streambed mining and extensive irrigated agriculture in the middle reaches, and river diversions altering sediment dynamics in the lower reaches. Adi et al. (2013) observed that a dramatic change in land use occurred between 1997 and 2004 which has led to high sedimentation rates in the reservoirs. Despite the extent of anthropogenic catchment modification, and in part because some anthropogenic effects offset others, pre-LUSI sediment yields in the Brantas system were “not very high on a global scale” (Jennerjahn et al., 2013). However with the eruption of the LUSI volcano and subsequent mud disposal, sediment yield increased by a factor of about four compared to the pre-LUSI levels. Before the input of LUSI mud, sediment concentrations in the Porong increased with increasing river discharge and wet season sediment concentrations were an order of magnitude higher than in the dry season. Average wet season flow was about 600 $m^3 s^{-1}$ with a peak of 1200 $m^3 s^{-1}$ during extreme wet year in 1984 (Hoekstra et al., 1989). Post-LUSI, this pattern is reversed with higher sediment concentrations in the dry season (Jennerjahn et al., 2013) the combined effect of little dilution by the low river flows and the high volumes of pumped LUSI mud. Thus, post-LUSI sediment concentrations and yields are maintained at relatively high levels throughout the year. Low stream flows are insufficient to flush LUSI mud from the estuary during the dry season when tidal flushing plays a relatively important role. Despite these marked changes in the Porong's sediment regime, rates of sediment delivery to the river mouth are still dominated by river discharge. Brantas River discharge at Mojokerto exhibits strong (about two orders of magnitude) seasonal variability (Adi et al., 2013; 1970–2003 data) and mean monthly flows varied seasonally by an order of magnitude during the study period (Fig. 3).

During the observation period, mean vertical accretion in the mangrove forests of the Porong River mouth during the wet season was 19.6 and 20.5 cm y^{-1} at Forests 1 and 2, respectively (Table 2). These mean values exceed the upper rates reported in the literature by a factor of 2. Reported short-term measurements of sediment accretion in mangrove forests range from 0 to 10 cm y^{-1} (Ellison, 1998; Alongi, 2009; Morrisey et al., 2010). Even in the dry season, vertical accretion rates in the Porong (5.5 and 4.0 cm y^{-1} at Forests 1 and 2, respectively) are comparable with the higher rates for mangrove forest soil accretion reported in the literature (Alongi, 2009; Morrisey et al., 2010).

Vertical accretion in the mangrove forests varied seasonally by a factor of four and was most strongly correlated with river discharge. The rate of mud disposal was not a significant determinant of vertical accretion rates, although the availability of large quantities of pumped LUSI mud underpins the high vertical accretion rates that occur during both wet and dry seasons. In the period prior to the LUSI eruption, deposition at the Porong mouth in the dry season is close to zero because of the flow diversion to the city of Surabaya at Mojokerto (Hoekstra, 1987) so the high dry season sediment accretion rates in the Porong mangrove forests measured in this study are almost entirely due to LUSI mud inputs.

The vertical accretion and surface elevation gain showed similar trends at both forest sites. Both forest sites were characterized by high vertical accretion and high rates of surface elevation gain. Rapid vertical accretion in both mangrove forests was associated with increasing surface elevation (Fig. 5), suggesting that sediment deposition is the most dominant process leading to the measured increases in surface elevation at the mouth of the Porong River. This result is similar to sites in Australia (Lovelock et al., 2011) and in the Pacific Islands (Krauss et al., 2010) where sediment inputs were also important to soil surface elevation gains. Sediment deposited above the surface is trapped, facilitated by aboveground roots (Spenceley, 1977; Furukawa and Wolanski, 1996; Young and Harvey, 1996; Krauss et al., 2003; Alongi, 2009), resulting in increased surface elevation (Krauss et al., 2003; Stokes et al., 2010). The role of sediment deposition as primary process controlling surface elevation change is also reported in salt marshes in Australia (Rogers et al., 2005). This is in contrast to sites in the Caribbean where plant root growth (root biomass) is the major contributor to surface elevation change (McKee et al., 2007; McKee, 2011).

Shallow subsidence rates within the forest sites ranged from 0.8–5.5 cm y^{-1}. These rates which are comparable with the high rates of shallow subsidence in Bayou Chitique, Mississippi River delta, which subsided 4.9 cm in two years (Cahoon et al., 1995). High rates of shallow subsidence probably occurred due to compaction, likely due to the high

Table 3
Characteristics of the sediments in the mouth of the Porong River. Values are means with standard errors. The level of replication varies with N from 3 to 40 and is reported within the table under the mean. Significant differences among means are indicated as follows: a — P < 0.5, b — P < 0.01, c — P < 0.001, d — P < 0.0001).

	Forest 1	Forest 2	Spoil island	LUSI mud
Bulk density (g m^{-3})	0.68 ± 0.02^d (N = 15)	0.74 ± 0.02^d (N = 14)	0.56 ± 0.02^d (N = 40)	1.50 ± 0.11^d (N = 5)
Total organic C (%)	1.06 ± 0.03^d (N = 9)	1.04 ± 0.02^d (N = 9)	0.55 ± 0.07^d (N = 24)	0.56 ± 0.01^d (N = 2)
Total N (%)	0.04 ± 0.01^a (N = 6)	0.08 ± 0.02^a (N = 6)	0.08 ± 0.01^a (N = 18)	0.05 ± 0.004^a (N = 5)
$\delta^{13}C$ (‰)	-23.7 ± 0.15^d (N = 9)	-23.4 ± 0.06^d (N = 9)	-22.0 ± 0.21^d (N = 24)	-20.6 ± 0.12^d (N = 3)
$\delta^{15}N$ (‰)	4.93 ± 0.07^b (N = 9)	5.03 ± 0.06^b (N = 9)	4.92 ± 0.10^b (N = 24)	5.80 ± 0.26^b (N = 3)
$\delta^{13}C$ LUSI mud: $\delta^{13}C$ mangrove	0.58	0.62	0.81	1.0

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rates of sediment loading (Meckel et al., 2007; Syvitski et al., 2009). In this case in large part because of the LUSI mud inputs.

The source of sediment contributing to soils in mangrove forests can be investigated by tracing the organic matter source using stable isotope analysis (Cifuentes et al., 1996; Dehairs et al., 2000). Sediment deposited in mangrove forests may contain a proportion of organic matter originating from *in situ* mangrove biomass (autochthonous) and organic material imported from other sources (allochthonous) (Cifuentes et al., 1996). The δ^{13}C composition of the mangrove soils (-23.7 ± 0.15 and -23.4 ± 0.06‰ in Forest 1 and 2, respectively) reflects the high contribution of LUSI mud into the mangrove sediments (Table 3), compared with other locations where the isotopic signature of carbon in mangrove sediment ranges from -27 to -28 ‰ (Cifuentes et al., 1996; Dehairs et al., 2000; Giarrizzo et al., 2011). The δ^{13}C results confirm the high allocthonous sediment input to the Porong mangrove forests, particularly that from the LUSI mud volcano.

4.2. Effect of high sedimentation on Avicennia sp. growth rates

The growth of trees was lower during periods with high sedimentation rates (Fig. 7). Mangrove tree growth rates during periods of low vertical accretion at Porong (0–10 cm year^{-1}) are relatively high and highly variable (47.3 ± 4.0 cm y^{-1}; N = 56, ±SE). At vertical accretion rates of 10–20, 20–30 and >30 cm y^{-1}, mean mangrove growth rates (±SE) are 16.6 ± 2.5 (N = 19), 9.8 ± 2.1 (N = 15), and 6.9 ± 2.6 (N = 8) cm y^{-1}, respectively. Thus, periods of low vertical accretion rate are necessary, but not the only factor contributing to high mangrove growth rates, i.e. during periods of low accretion rates, mangrove growth is highly variable, ranging from zero to 129 cm^2 y^{-1}, whereas during periods of high accretion rates, mangrove growth is always low and high growth rates were not observed. Thus, vertical accretion rates may establish a potential growth envelope for genus *Avicennia* in this setting, limiting but not determining the rate of tree growth. Based on the regression analysis *Avicennia* growth in the Porong River mouth is predicted to cease at vertical accretion rates of 38.6 ± 3.9 cm y^{-1}.

In the present study, the growth of mangroves showed a seasonal pattern. Cessation of tree growth occurred at the highest sedimentation rates in the wet season therefore suggesting that the ecosystem is vulnerable to high sedimentation rates. Higher sediment deposition, particularly during the wet season, is likely to have been the main factor causing lower growth rates through its role in reducing oxygen levels in roots. High rates of sediment supply can cover pneumatophores, which causes oxygen deficits in the root zone as transport from air to within the root tissues belowground is prevented as transport from air to within the root tissues belowground is prevented (McKee and Mendelssohn, 1987). As mangrove rely on ventilation by pneumatophores in situations where poor soil aeration occurs (Saenger, 2002) high sedimentation can result in declines in tree growth, potentially culminating in tree death (Jimenez et al., 1985; Ellison, 1998). Several studies have reported mangrove mortality due to buried pneumatophores, for example, at Point Samson, Gladstone and at Bowen in Australia (Ellison, 1998). In addition to covering pneumatophores, LUSI mud is also very low in organic matter and nutrients (Table 3) which may also contribute to low growth rates during periods of high vertical accretion (Reef et al., 2010). An additional contributor to reduced growth in the wet season may be reduced light levels due to high cloud cover, which has been indicated to limit primary production in tropical forest in the Americas (Graham et al., 2003). However, in mangroves in Micronesia tree growth was enhanced with higher levels of rainfall, possibly due to associated decreases in root zone salinity (Krauss et al., 2007). Although nutrient and light availability may influence growth rates, the correlation among vertical and reduced tree growth indicates that sedimentation is an important factor limiting growth when sediment concentrations in the river are very high. Despite the very high level of sediment supply, mangroves are extensive at the Porong River mouth. Abundant supply of fine-grained sediment and freshwater discharge provide a suitable substrate for mangrove forest development (Lovelock et al., 2007; Alongi, 2009; Lovelock et al., 2010). Mangroves develop in sheltered areas where fine sediments accumulate; the trees develop extensive root systems that capture and consolidate sediments (Spenceley, 1977; Furukawa and Wolanski, 1996; Young and Harvey, 1996; Krauss et al., 2003; Alongi, 2009). In addition, the root systems play a role in morphological adaptation to anoxic substrate conditions (McKee and Mendelssohn, 1987; McKee, 1996). Saenger (2002) showed that in both seedlings and adult plants the development of aerenchyma tissue in above and below ground roots may serve as an oxygen reservoir, or as a system which allows the maximum volume of root per quantity of living tissue, thereby achieving economy in oxygen consumption per unit volume. Among mangroves, mature *Avicennia* is recognised as one of the mangrove genera most tolerant of high sedimentation rates (Vaiphasa et al., 2007), while young *Avicennia marina* plants have the highest root porosity of 45.7% in comparison to other mangrove species (e.g. *Rhizophora stylosa*, *Bruguiera gymnorhiza* and *Aegiceras corniculatum* with porosity of 27.9%, 30.0%, 27.4%, respectively) (Youssef and Saenger, 1996).

Mangrove adaptation to high sedimentation at the study sites can be explained by their allocation of resources to support growth of pneumatophores and the characteristics of their shallow root systems. Pneumatophores remained exposed to the atmosphere despite high sedimentation, allowing oxygen diffusion in the roots (see Supplementary Fig. 2) and indicating that pneumatophore growth at our study site was clearly sufficient to keep pace with the high sediment deposition rates, although root growth may have been supported at the cost of sustained aboveground growth in the wet season when sedimentation rates were particularly high. The structure of pneumatophores of *Avicennia sp.* may enable trees to acclimate to low oxygen conditions (Ball, 1988; Pi et al., 2009). Studies of root structure have shown that *Avicennia sp.* roots respond to hypoxic conditions by increasing the above ground length of pneumatophores (Dahdouh-Guebas et al., 2004, 2007; Purnobasuki, 2013) and thus the flexibility of the root system of *Avicennia* may permit its survival under the extremely high sedimentation rates observed in the Porong River.

Below the surface, most mangroves possess a laterally spreading cable root system with smaller, vertically descending anchor roots that bear fine nutritive roots (Saenger, 2002). The ability of *Avicennia sp.* to keep up with high sedimentation at the Porong River mouth may be also associated with high rates of root production of this species that allow mangroves to maintain their growth in sediment rich environments. The high level of root production at our site is reflected in the carbon isotopic signatures observed in the mangrove sediments (Table 3), which indicate that sediment carbon is partly from mangrove-derived source, i.e. roots. The proportion of root production to mangrove-derived carbon source in this site is expected to be higher than leaf litter contributions as the site has high rainfall and tidal exchange, both which are correlated with high rates of leaf litter export (Adame and Lovelock, 2011). However, this finding needs to be confirmed by root biomass and production assessments. The complex root systems of *Avicennia* are likely to facilitate organic matter deposition due to high investment in pneumatophores which are proposed to be produced at a density that maintains aeration, balancing the negative effects of sediment accretion (Young and Harvey, 1996).

5. Conclusion

High rates of sedimentation occurred in the mangrove forests at the mouth of the Porong River with accumulation of up to 20 cm y^{-1} and dry season rates of about 5 cm y^{-1}. The higher rates of vertical accretion occurred in the wet season when larger river discharges transported high volumes of sediment with a high component of pumped LUSI mud. Even during the dry season when little river flow occurs, vertical accretion rates remain high, relative to rates reported from elsewhere, due to tidal transport of LUSI mud pumped to the river. At high rates of vertical accretion reported in this study, *Avicennia sp.* in the Porong River grew in basal area at 14.2 $cm^2\ y^{-1}$ (Forest 1) and 10.9 $cm^2\ y^{-1}$ (Forest 2). *Avicennia sp.* showed reduced growth in response to the extremely high rates of vertical accretion in the wet season and our line of best fit indicates that, in this environment, cessation of growth at vertical accretion rates of 38.6 ± 3.90 $cm\ y^{-1}$. Our results establish a potential growth envelope for *Avicennia* in the Porong River setting, with vertical accretion rates limiting growth at high rates of vertical accretion. The long term rapid sedimentation in the mouth of Porong River and the capacity of *Avicennia sp.* to adapt in this environment is probably due to the rapid growth of their highly adapted root systems which may permit persistence of the *Avicennia sp.* mangrove under high levels of sediment inputs.

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