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Subsidence reveals potential impacts of future sea level rise on inhabited mangrove coasts

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Human-induced land subsidence causes many coastal areas to sink centimetres per year, exacerbating relative sea level rise (RSLR). While cities combat this problem through investment in coastal infrastructure, rural areas are highly dependent on the persistence of protective coastal ecosystems, such as mangroves and marshes. To shed light on the future of low-lying rural areas in the face of RSLR, we here studied a 20-km-long rural coastline neighbouring a sinking city in Indonesia, reportedly sinking with 8–20 cm per year. By measuring water levels in mangroves and quantifying floor raisings of village houses, we show that, while villages experienced rapidly rising water levels, their protective mangroves experience less rapid changes in RSLR. Individual trees were able to cope with RSLR rates of 4.3 (95% confidence interval 2.3–6.3) cm per year through various root adaptations when sediment was available locally. However, lateral retreat of the forest proved inevitable, with RSLR rates up to four times higher than foreshore accretion, forcing people from coastal communities to migrate as the shoreline retreated. Whereas local RSLR may be effectively reduced by better management of groundwater resources, the effects of RSLR described here predict a gloomy prospect for rural communities that are facing globally induced sea level rise beyond the control of local or regional government.

Land subsidence has recently been recognized as an important magnifier of relative sea level rise (RSLR), with land subsidence rates on average four times higher than global sea level rise in many places along global coastlines[1]. Locally, the effects can be even stronger[2], causing whole cities to sink with multiple metres (for example, maximum reported subsidence[3] of 1 m, 2 m and 5 m for Jakarta, Bangkok and Tokyo, respectively). Many places that are subjected to subsidence-induced exacerbation of RSLR are productive low-lying areas near deltas and

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coastal cities where industries often remove large amounts of ground water[2,4,5]. The combination of water, oil or gas extraction and the weight of the coastal city on top of soft alluvial deposits can cause urban areas to sink[5,6]. The rate of subsidence can be reduced through strict regulation of groundwater extraction, as has been shown in the case of Tokyo[7]. However, in many countries this intervention proves difficult for multiple reasons, most commonly because alternative water sources, such as seawater and surface water, are either too polluted[8], requiring a drastic improvement of basic sanitation and domestic waste management first, or too expensive and energy consuming (for example, desalinization of seawater[9]). The effect of subsidence on RSLR is found strongest in South East Asia, with poor surface water quality[10] and many megacities near the coast[1,11].

For many countries in this region, adaptation to problems caused by RSLR is currently the only option, but it comes with challenges. The most common adaptation response to rising water levels is heavy investment in conventional flood defence structures, such as sea walls and dykes to protect the low-lying hinterland from the sea and rivers[7,12]. These are often accompanied by the creation of expensive and high-maintenance polders and associated pumping systems to get the water out. However, if the effect of land subsidence extends towards the intertidal area, coastal flood defence structures will also experience exacerbated RSLR (Fig. 1 (2))[12,13], increasing the risk on levee failure, and thus magnifying maintenance costs, such as heightening the crest and fortifying the base of the structure[12].

So far, subsidence research has largely focused on urban areas, where the problem often originates. Only few studies have investigated how subsidence-aggravated RSLR affects the wider alluvial plain and the people living there (Fig. 1 (1))[5,14]. However, subsidence effects are expected to occur in the rural area, as aquifers from which groundwater is extracted often extend far beyond urban boundaries. The impact of RSLR on rural areas may be even worse than on cities, as rural areas often lack the financial means for conventional flood defence structures. These areas then depend on existing, but degraded, coastal ecosystems to minimize effects of storms, waves and erosion[7,15,16].

Vegetated foreshores, including mangroves and salt marshes, can attenuate waves[17–20], and reduce the probability and impact of dyke breaches[21]. Because these foreshores can trap sediment and/or form peat[22], they can keep up with reasonable rates of RSLR provided that sufficient sediment is available[23–25]. However, it is yet unclear how RSLR in vegetated foreshores compares with RSLR on land, where buildings press down on the sediment (Fig. 1 (2)). If vegetated foreshores adapt to rapid RSLR, they may be a key component in maintaining coastal resilience in areas where conventional coastal protection structures cannot be installed or maintained. In this Article, using two novel and low-cost methods to approximate RSLR, we demonstrate how 20 km of rural coastline and its vegetated foreshore, neighbouring a rapidly subsiding city, are affected by rising water levels (Fig. 1). We discuss the implications of mangrove presence for the resilience of coastal communities under pressure of globally induced RSLR.

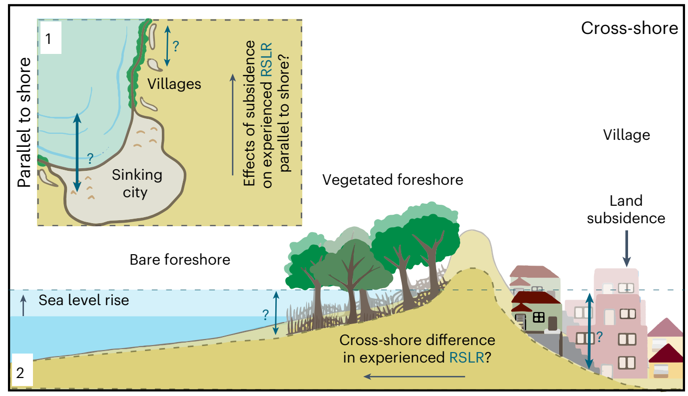

Fig. 1 | Hypothesized gradients in experienced RSLR (that is, the change in water level experienced at a certain location). Experienced RSLR is a combination of various processes such as sea level rise, where the average sea level increases over time (dashed blue line indicates risen sea surface), and land subsidence and compaction, where the current land level (transparent beige profile) sinks to a lower level over time (dashed beige profile). The effects of land subsidence induced by groundwater extraction at coastal cities may propagate parallel to the shore and can still be experienced as substantial RSLR in adjacent rural areas and villages (1). The effects of land subsidence may still be experienced as substantial RSLR at the foreshore, which can threaten urban and adjacent rural flood defence structures (2).

Results

City subsidence propagates to adjacent coastal communities

In Demak (North Java, Indonesia), decades of land subsidence caused by industry in the adjacent city Semarang[26] (Fig. 2a) have led to extreme land loss (496 ha (ref. 27), Fig. 2b). Census data at the level of villages in Demak District[28] show that the advancement of the sea and increasing flood frequency forced up to 30% of the people living in coastal villages to move to inland areas (Fig. 3a), which are generally more crowded (Fig. 3b). Structured interviews that were conducted among a total of 194 households of 14 coastal villages along 20 km of coastline revealed that the remaining people are adapting to increased flood frequency through periodic heightening of their houses' ground floor, here used as a low-cost proxy for RSLR (Fig. 3c). We obtain an approximation of the net RSLR experienced by these villages by looking at raising of ground floors in centimetres over the amount of time. While houses sink over time, the floor and surrounding land (streets and gardens) are regularly elevated to prevent frequent flooding. Thus, as the house sinks over time, the roof gutter becomes situated closer to the surrounding ground level over time (Fig. 3c). We used the height of the roof gutter as a measurable validation for these floor heightening recollections by households. This method cannot be used to distinguish the relative contribution of underlying processes that result in net RSLR (such as absolute sea level rise, shallow subsidence processes and deep subsidence processes), but it does provide a value for the RSLR as it is experienced at the location of each house: experienced RSLR. The experienced RSLR that we obtained with this method ranges from approximately 5–20 cm per year near Semarang to 0–2 cm per year near the Wulan Delta, 20 km further north-east along the coastline (Fig. 3d). Therefore, the RSLR experienced in the villages near Semarang corresponded to previously reported values for subsidence in the area, which range from around 8 cm per year (refs. 2,29,30) up to 20 cm per year (refs. 31,32). This shows that, in areas with extreme subsidence, measurements of RSLR can be obtained with relatively low-cost methods, which also opens the possibility to do comparable data collection in other data-scarce regions.

Land subsidence is experienced by mangroves as RSLR

The propagation of RSLR through soil subsidence from urban to rural coastal area not only affected landward parts that are not regularly flooded but was also measured in intertidal areas. To quantify the change in water level that trees in the intertidal zone experienced, we conducted several field surveys in which we attached small water level loggers to mangrove tree trunks for a period of 2 years, which rendered a continuous water level dataset of 1.25 years. We assumed that, if the trees would experience subsidence in the same order of magnitude as it has been reported in the city, this should be visible in an increase in average water levels relative to the tree. This method does not measure RSLR compared with a fixed datum and therefore cannot help distinguish underlying processes that drive long-term mangrove forest floor elevation changes relative to that datum, as can be done with deeply anchored RSET installations[24,33]. However,

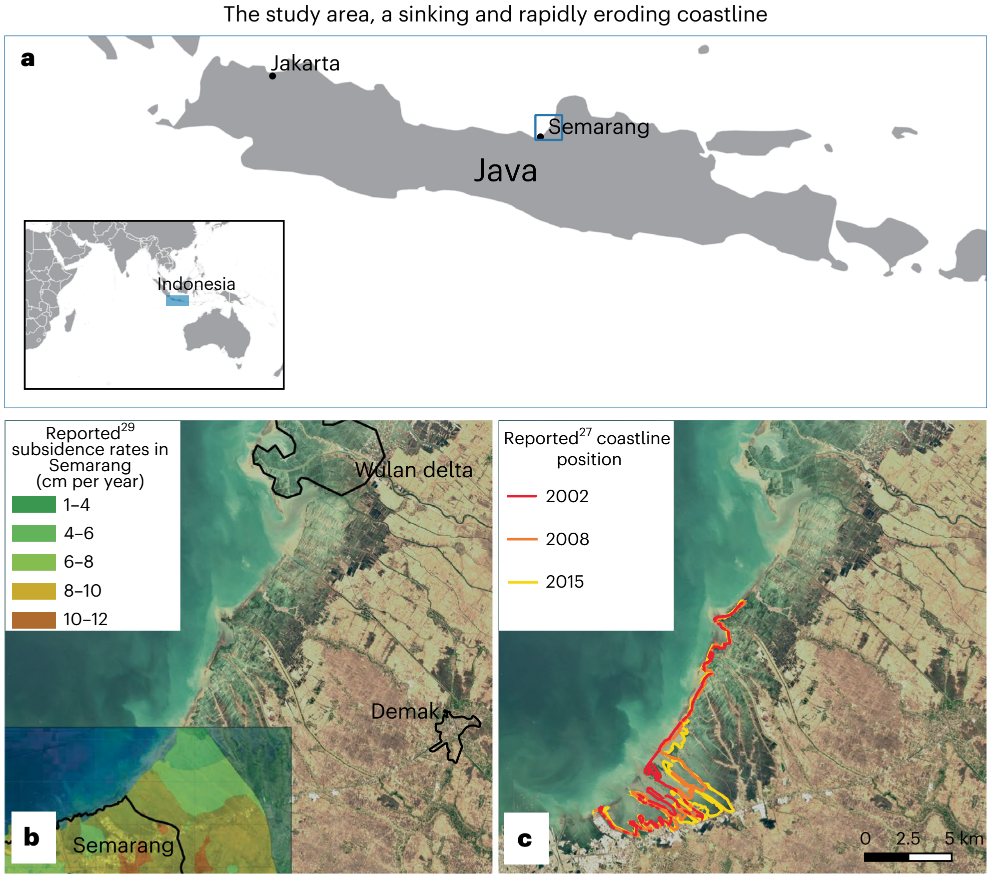

Fig. 2 | Situation overview of the study area based on previously reported subsidence and erosion rates. a, The coastline of Demak, located next to the City of Semarang on the north coast of Java, Indonesia, has seen substantial erosion over the past decades. **b**, Satellite imagery (Sentinel-2) of the study area: the coastline of Demak District, Demak City is outlined in black. The study area comprises the rural coastal area that stretches from the coastal plain East of Semarang (−06°56′47.40′ S, 110°26′45.46′ E), to the Wulan Delta 20 km to the north-east (−06°44′55.54′ S, 110°33′57.70′ E), both outlined in black. The overlay map in the lower-left corner is a map made by EO4SD[29] and depicts subsidence rates of the area, obtained from radar satellite imagery, which are among the more conservative in literature. **c**, Coastline retreat experienced in the research area between 2002 and 2015; these specific shoreline positions have been reported by Ervita and Marfai[27] and are here superimposed on the same satellite image used in **b**.

this simple and relatively low-cost method revealed that mangrove forests do experience RSLR, which diminishes along the coast with distance from the subsidence epicentre, that is, the harbour area of Semarang (Fig. 4a). This trend of exponential decrease in experienced RSLR with increasing distance from the subsiding city was similar to the experienced RSLR gradient observed in the villages (Figs. 3d and 4a). Of course, both datasets come with some uncertainties related to, for instance, the relatively short measurement time in mangroves, and to household adaptation choices in the house dataset (for example, differences in house foundation depths, choices in terms of floor raising amounts and timing, and so on). These uncertainties are reflected in the relatively wide error bars for average experienced RSLR. However, the similar trends in experienced RSLR along the shore suggest that mangroves are subject to the same underlying processes, most likely related to land subsidence, that cause villages to experience an increase in sea level. The house floor dataset revealed that increasing water levels have been experienced by people over the past decades, which makes it likely that also mangroves have already experienced an increase in water levels over a longer period of time than the 1.25 years that we monitored. However, during the period that was monitored it appears that mangroves experienced significantly less rapid RSLR than village houses (Fig. 4a, $R^2 = 0.9$, $F = 62.7$, degrees of freedom (d.f.) 2 and 12, $P < 0.0001$). For instance, experienced RSLR in the village closest to Semarang was on average 8.2 cm per year (95% confidence interval (CI) 6.0–10.4 cm per year) and experienced RSLR of mangroves in the same area was 'merely' 4.3 cm per year (95% CI 2.3–6.3 cm per year) on average (Fig. 4a). The cause of this difference might be explained by many factors, such as the different time scales over which the sea level rise was experienced, differences in anchoring depth between houses and trees, absolute weight, pressure per square metre that the objects exert on the sediment, or compaction rates of intertidal versus supratidal sediment. However, even if the relative water level change that individual mangrove trees experience is less extreme than the change experienced by villages, it is still an order of magnitude larger than sea level rise that the trees would experience based on observed global trends in sea level rise (3.8 mm per year).

Intertidal RSLR drives foreshore and shoreline erosion

With insufficient sediment deposition to compensate for RSLR, the relative deepening of the intertidal area may induce vertical foreshore erosion, further deepening the foreshore. This indeed seemed to be the case in Demak, where the foreshore 50 m in front of the mangrove fringe was consistently deeper at sites close to the subsidence epicentre than at sites further along the coast (Fig. 4b, $F = 5$, $R^2 = 0.21$, $P < 0.05$). Such deep foreshores exert less bottom friction on waves and therefore allow more wave energy to reach the shoreline[34]. Especially with steep elevation change from foreshore to shoreline (a concave profile), deeper foreshores cause waves to come closer to the shoreline[35], which can further excavate the foreshore bed[36]. Erosion monitoring of the bare foreshore, 50 m seaward of the mangrove fringe, indeed revealed that

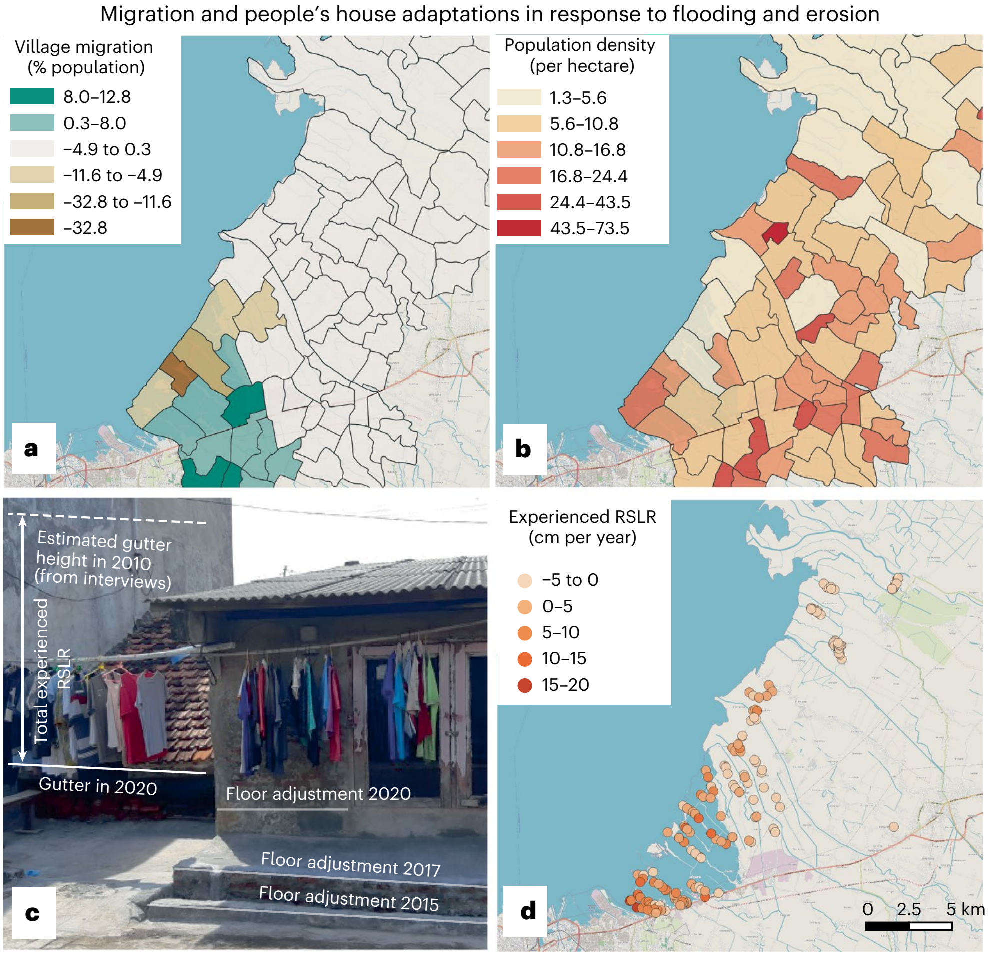

Fig. 3 | Observed responses of local communities to increasing flood intensity and coastal erosion. a,**b**, Migration fluxes in percentages of the village population in the year 2010 following coastline retreat depicted in (Fig. 2c). People seemingly migrated from the coastal villages towards villages further inland (**a**), where population densities (**b**) are higher. **c**, A house of a household from one of the frequently flooded villages. The process of raising the ground floor every so many years by a certain amount, without roof adjustment, leads to houses with gutter heights close to street level after one decade. We used these house adaptations over time to quantify the RSLR experienced by households. The year labels in this particular picture are indicative and merely meant to illustrate the process of floor raising over time. Photo: courtesy of Paksi Muhammad Herlambang. **d**, The RSLR rate (cm per year) experienced by households in the coastal area, based on floor adjustments and gutter height data (**c**).

deeper concave foreshores showed more substantial vertical erosion rates (Fig. 4b, $F = 4.8$, $R^2 = 0.2$, $P < 0.05$) than sites further away from the city (Fig. 4b), which tended to have shallower foreshores with a more gentle transition from foreshore to shoreline.

Besides vertical erosion of the foreshore, increased wave energy at the shore can also remove sediment between mangrove roots and thereby cause mangrove retreat. The result of this lateral erosion process is reflected in the mangrove mortality data. Both mortality of monitored aerial roots (estimate 0.08, standard error (SE) 0.02, z value 5.4, $P < 0.001$, Fig. 4c, grey), and the number of dead trees per 50 m coastline stretch (estimate 0.02, SE 0.004, z value 4.9, $P < 0.001$, Fig. 4c, black) increased significantly with foreshore depth along the experienced RSLR gradient. Deep and concave foreshores have been associated with lateral coastal erosion[37] and mangrove retreat[36,38,39]. This suggests that RSLR in combination with a sediment deficit instigates a self-reinforcing process of lateral coastal erosion (Fig. 5c).

Mangrove trees respond to rapid RSLR with root growth

Sites that experienced RSLR and rapid erosion of the foreshore also experienced high deposition rates inside the mangrove fringe (Fig. 4d). A similar process is frequently observed along vegetated foreshores where lateral cliff erosion occurs, creating ridges of accumulated sediment along the remaining marsh edge[40,41]. These ridges are created by deceleration of currents when water enters the vegetation, causing the suspended sediment to sink to the bottom in the first few metres of the marsh or mangroves[42,43]. Our data suggest that, in areas characterized by shoreline retreat, sediment supply to the mangrove fringe is high, and most likely originates from local foreshore erosion, as sediment deposition inside the mangrove fringe tended to be higher at sites where the bare foreshore was deeper (estimate −0.02, SE 0.01, d.f. 20, t value −1.4, $P = 0.16$) (Figs. 4b,d and 5c).

At sites that experienced the most rapid RSLR, vertical accretion in the fringe was sufficient to keep the local forest floor at a constant elevation relative to the water level measured at the tree stem (Fig. 4d). In principle, under these conditions, individual mangrove trees should be able to outgrow extreme RSLR rates, provided that they are able to withstand rapid sedimentation rates. In the field, we observed that sediment deposition in the fringe is often not a gradual process and can occur in rapid deposition events, for instance during a storm. During such events, mangroves seedlings and trees in the fringe can experience decimetres of sedimentation (Extended Data Fig. 1). Mangroves thus need to be able to survive such sedimentation events to be able to keep pace with the bed-level following RSLR. A manipulative field experiment in which we applied treatments of 0 cm, 20 cm and 40 cm

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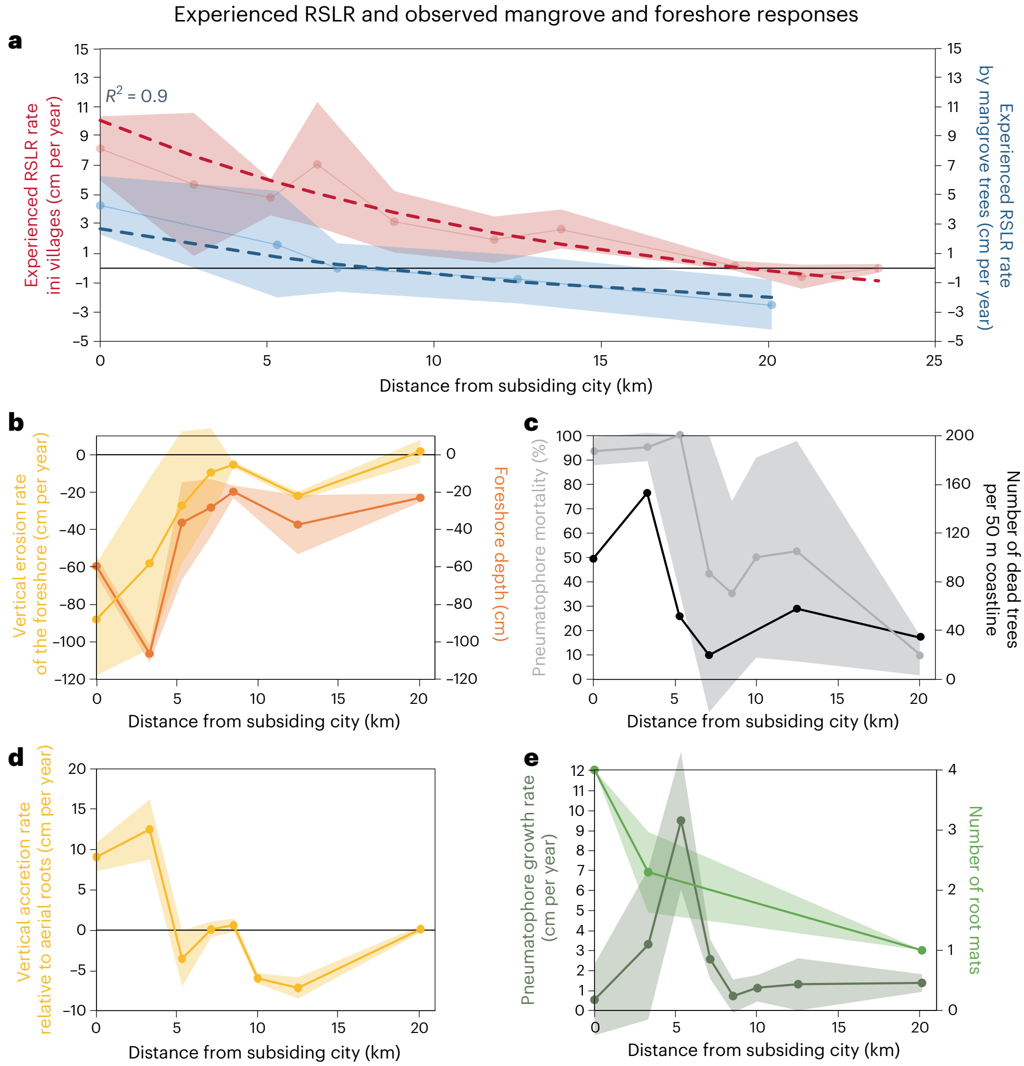

Fig. 4 | Parameters measured in the mangrove fringe and foreshore of Demak Regency, the rural area neighbouring Semarang City. Line colours reflect the type of variable: yellow tones for sediment, grey/black for mortality and green tones for plant-growth parameters. The subsidence epicentre (that is, the rapidly subsiding harbour area of Semarang) is distance 0 on the *x* axis. **a**, Average village experienced RSLR rate (cm per year) (±95% CI) and mangrove experienced RSLR rate (cm per year) (±95% CI) measured over 1.25 years with pressure loggers attached to mangrove trees fringing the shore. The adjusted R^2 value and fitted curves from the log-linear model, testing the effect of cross-shore zone (village versus mangrove) and distance from epicentre (km) on experienced sea level rise are plotted on top of the observed values **b**, Average (±95% CI) vertical foreshore erosion rate and average (±95% CI) foreshore depth relative to mean sea level. Both parameters were measured periodically over a period of 1.5 years at sedimentation poles located 50 m offshore from the mangrove fringe along the subsidence gradient. **c**, Primary *y* axis: average (±95% CI) pneumatophore mortality (%) in the mangrove fringe at the end of the 1.5 year monitoring period. Secondary *y* axis: number of dead trees observed per 50 m mangrove fringe at the start of the monitoring period. **d**, Average (±95% CI) sediment accretion/erosion (cm per year) relative to marked pneumatophores of mangrove trees in the fringe along the subsidence gradient monitored for a period of 1.5 years. **e**, Primary *y* axis: average (±95% CI) pneumatophore extension rate (cm per year) monitored in the mangrove fringe over a period of 1.5 years. Secondary *y* axis: number of root mats that living trees had grown over their lifetime in the fringe.

of sediment to the root zones of saplings and young mangrove trees (Extended Data Fig. 2) confirmed that mangroves can survive sudden sedimentation events of 20 cm. In addition to this experiment, we conducted an observational study on root zones of mature mangrove trees in the fringe at various distances from the subsidence epicentre to understand how trees had adapted to the rising water levels over their lifetime (that is, quantification of subsurface remnants of old cable-root and pneumatophore layers (root mats)) and if current differences in pneumatophore elongation could be observed between sites with rapid and less rapid experienced RSLR. This dataset revealed that one of the mechanisms by which trees may cope with buried and frequently inundated pneumatophores is through investment in new root mats: that is, the growth of new lateral cable roots in a fresh sediment layer, from which new pneumatophores can grow upward (Fig. 5c and Extended Data Fig. 3a). Trees that experienced rapid RSLR—and high sediment accretion rates in the fringe (Fig. 4e, distance <5 km)—had grown significantly more root mats over their lifetime than trees that had experienced lower RSLR rates (estimate 0.2, SE 0.1, *z* value 2.1, $P < 0.05$) (Fig. 4e, distance >5 km). The coping mechanism to keep up with slowly rising water levels without sediment accretion seemed to be through pneumatophore extension (Fig. 5d and Extended Data Fig. 3b), as pneumatophore growth increased significantly with higher experienced RSLR rates at the sites with stable or slightly eroding forest-floors (estimate 0.15, SE 0.05, d.f. 10, *t* value 3.0 $P = 0.01$; Fig. 4e, distance >5 km). These results suggest that, if enough allochthonous sediment is available, mangrove trees can cope with experienced RSLR rates of 4.3 cm per year (95% CI 2.3–6.3 cm per year), at least over the time scale of several decades based on the age of the forests in this area

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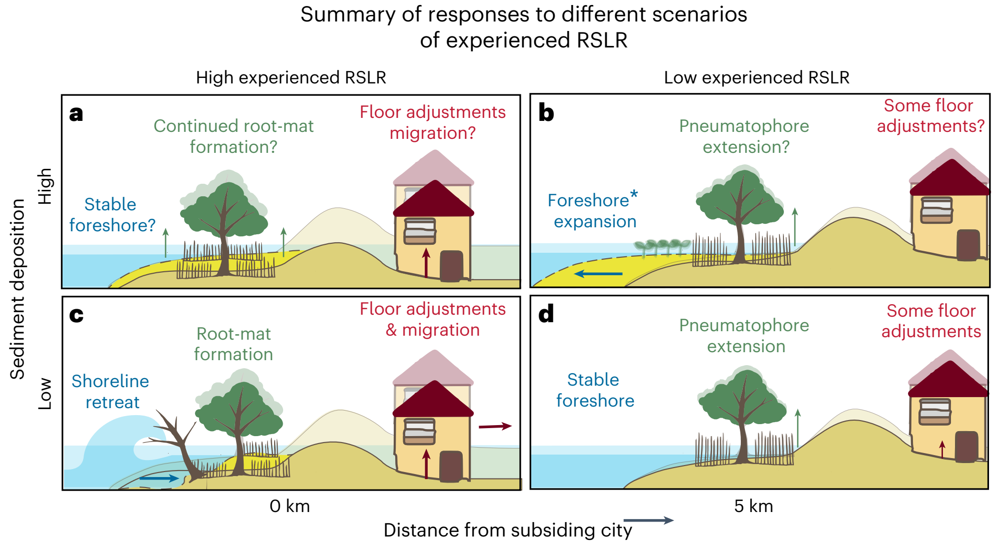

Fig. 5 | A summarizing schematic representation of the key processes affecting cross-shore profiles under low and high RSLR rates (columns), in the presence of low and high sediment availability (rows). The transparent profiles in the background represent pre-subsidence profiles. The solid lines and figures represent sunken profiles. Sea level rise is represented by the translucent water level above the blue water level. The dashed lines represent sedimentation (yellow) or erosion (transparent (only in **c**)). **c** and **d** are based on situations as we have observed at our study site at 0 km and 5 from the subsiding city. **a** and **b** are hypothetical scenarios and expected effects based on literature (*). **a**, Vegetated foreshores are expected to remain stable if the sediment availability matches RSLR at the foreshore[5]. Trees may survive RSLR and sedimentation rates by forming new root mats in freshly deposited sediment, but long-term survival under these conditions is unsure. Under these conditions, migration of people is not expected, as the shoreline remains stable, but flooding will probably continue to occur. **b**, When RSLR is low and sediment supply is high, foreshores tend to expand[5,44]. Coastal communities are probably not severely affected by RSLR under these conditions although flooding might still occur **c**, Under high RSLR rates (0–5 km from Semarang), sinking foreshores accommodate higher waves, which erode the local bare foreshore and deposit sediment inside the mangrove fringe. Trees in the fringe initially survive due to the local sediment input in which they can create new root mats but will inevitably die when the coastline retreats due to lateral erosion. Coastline retreat and frequent flooding will affect people and drives them to adapt or move **d**, Pneumatophores extend with rising water levels, under low to moderate RSLR rates and limited sediment supply. People may adjust their floors in response to floods.

(Fig. 5a). Such high sedimentation rates have been reported at forest scales in unique situations[44], but generally most deltas that experience RSLR have a sediment deficit[5]. Under the latter conditions, sedimentation rates might be high in the forest fringe (Fig. 5c), but vertical forest floor accretion will probably not match RSLR throughout the entire forest. In most cases, mangrove systems as a whole are therefore likely to retreat when RSLR surpasses the previously reported threshold of 6 mm per year, which is based on mangrove sediment records over the last deglaciation period[23]. The data on response of mangrove trees that we present here suggest that, under such continued RSLR, mangrove system survival depends on system-wide limitations related to sediment availability and transport, instead of the physiological response of individual trees.

Discussion

Implications for sustainable flood defence under rapid RSLR

Our data demonstrated that individual mangroves are resilient to RSLR with high sediment deposition. However, a sediment deficit with respect to RSLR ultimately leads to deepening of the foreshore, increased wave impact on the shoreline and mangrove die-back (Fig. 5c). Also, in literature it is confirmed that coastal mangrove fringes are more stable with shallow and convex foreshores[38,45]. This opens opportunities for maintenance and restoration of foreshores to maintain mangrove forests. In non-subsiding but eroding regions, a convex and shallow profile can be restored through the placement of permeable structures parallel to the coastline, to trap the available sediment and thereby elevate the foreshore bed[46]. In Demak, this method has led to sediment accumulation directly seaward of the mangrove fringe, resulting in local coastline stabilization[47]. However, to truly restore an eroded, concave foreshore profile to a convex foreshore profile, an additional amount of sediment is required (Fig. 5a), and even more sediment is required to elevate the bed enough to cause coastline progradation similar to non-subsiding scenarios (Fig. 5b).

In the case of Demak, a simple calculation based on historical coastline progradation data ('Sediment deficit calculation for Semarang' in Methods) suggests that the sediment accretion in the early 1900s, before the onset of subsidence, used to be around 9 mm per year. Assuming that this would be the maximal restorable sediment input into this system, a sediment deficit would still be present with the RSLR rates that the area experiences today. Similar trends have been observed in deltas worldwide, where subsidence and reduced sediment supplies from rivers (for example, due to upstream dams and canalization) resulted in coastal retreat[5]. If a positive sediment balance cannot be restored, mangroves need space (that is, a gentle slope on the landward boundary) to move landward to survive rapid RSLR. These findings are supported by recent saltmarsh studies, which demonstrated that marshes are resilient to SLR with high suspended sediment concentrations, but relied on landward transgression to survive under low sediment inputs[25]. This presents a societal problem: most low-lying rural coastal areas are highly productive and densely inhabited, so 'unoccupied' space for landward migration is not easily available.

The future of coastal communities facing rapid RSLR

Urban areas that are subject to subsidence aggravated RSLR are often exposed to frequent river and tidal flooding, which can become a severe nuisance in areas where run-off can no longer be drained to the sea. Subsiding cities, however, have the economic power to adapt to these problems (for example, Jakarta giant sea wall[48]), at least partly supported by the extracting industries that are at the base of the subsidence problem. The externalization of environmental costs from the city to the surrounding rural areas is an equity problem with potentially

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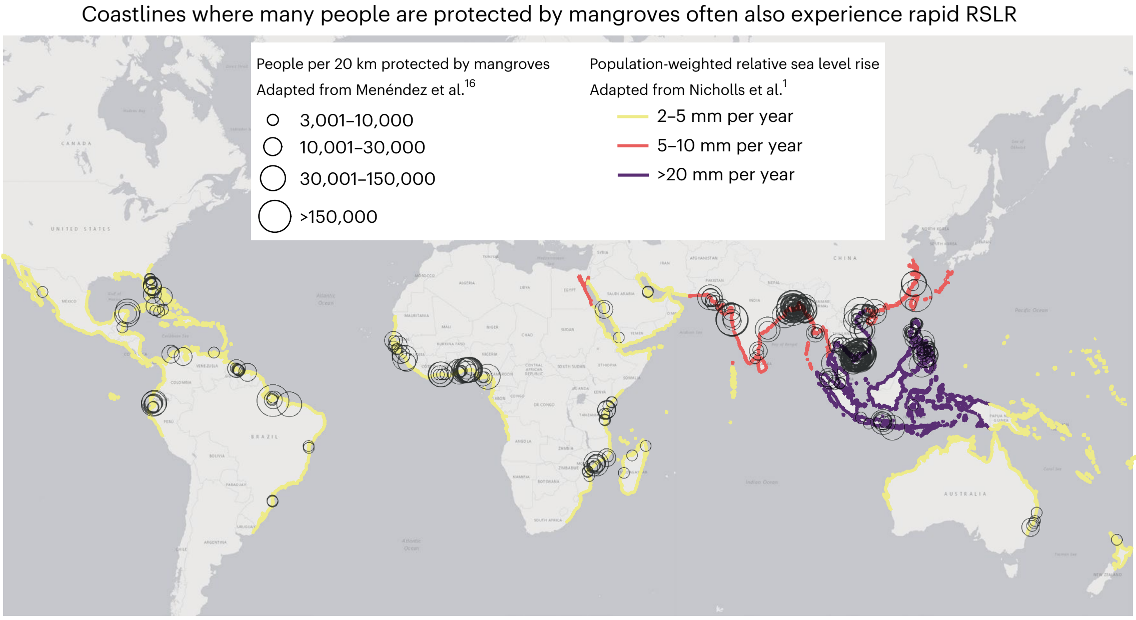

Fig. 6 | Overlay map of existing data on relative sea level rise and people protected by mangroves. An overlay of data presented in the recent studies by Nicholls et al.[1] and Menéndez et al.[16] suggests that coastal populations that experience the most severe RSLR (average population-weighted RSLR, adjusted from Nicholls et al.[1]) are also the populations that currently rely the most on mangroves for protection against cyclones and storms surges (people per 20 km protected by mangroves, adapted from Menéndez et al.[16]). The average population-weighted RSLR is a dataset produced by Nicholls et al.[1] and is available in ref. 57. This dataset was used here under the CC BY 4.0 licence. The only adjustment that we made is that data on RSRL outside mangrove regions are not displayed in this figure. The number of people per 20 km coastline protected from cyclones is one of the datasets produced by Menéndez et al.[16] (dataset 'MANGLAR_Global_TESELA_AEB_TC' available in ref. 58) and was used here under the CC BY 4.0 licence. The only adjustment made is that coastal populations below 3,000 people per 20 km coastline are not displayed to ensure visibility of the RSLR lines.

large social, financial and even legal implications. Unlike people within the city's boundaries, rural communities are often not protected by expensive advanced flood defence structures and associated polders and pumping systems. Instead, a recent study[16] estimated that, worldwide, 11.9 million people are currently protected from cyclones by mangroves, and this especially applies to rural communities near cities[16] (Fig. 6). Moreover, 46% of these coastal communities live in regions that are reportedly subject to average RSLR rates of more than 2 cm per year (Fig. 6). These communities already face frequent flooding, which will only increase in intensity and frequency with rising sea level. Migration and floor raising data from our study suggest that people generally respond to frequent flooding in two ways (Fig. 5c): fight (that is, keep the water out of the house) or flight (move further land inward or elsewhere). These adaptation strategies have been reported in previous studies, focusing on how flood-prone communities can improve their adaptation strategies[49,50]. In one of those studies[50], 55% of the interviewed respondents of flood-prone coastal communities indicated not to be able to move to higher grounds due to financial limitations. In addition, social limitations can play a role, as land ownership and income source (for example, fisheries) may bind families to the coast[50].

Overall, our study shows how rural communities on the margins of populous cities will suffer the negative impacts of RSLR unless their more affluent neighbours address the subsidence related problems through an integrated landscape approach. Local governments may for instance implement an integrated coastal management strategy, linking hard infrastructure and vegetated foreshores along a gradient from rural to urban areas; optimize sediment input and retention in the system[51]; and implement integrated water resource management plans that limit ground water extraction to reduce subsidence. With such measures, local governments can directly influence how their region will experience sea level rise. If RSLR is not addressed in this integrated way, the current local-scale refugee crisis observed in our study site will continue to unfold, as many rural communities worldwide (Fig. 6) are left with little choice but to retreat landward. In this respect, the present study offers a future perspective on the fate of global coastal communities under accelerated global sea level rise.

Methods

Village migration data

Village migration and population density data were obtained from the website of the central bureau of statistics of Demak Regency[28]. The oldest census data available at village level were from 2009, with arrival and departure data per village available for every 5 years since then. Published shoreline change data[27], and a timeline search in Google Earth Pro (version 7.3.3.7786) for the area near Semarang, showed that in 2009 a major shoreline change occurred, which would probably have affected the livelihood of the local communities. We therefore decided to use the migration data at village level from 2009 to 2010 to investigate how many people moved away from the area after the event. The migration flux was calculated by the following equation:

$$\text{Migration flux}\,\% = \frac{\text{arrivals} - \text{departures}}{\text{population}} \times 100$$

This equation gives negative percentages when a proportion of the village population left, and positive values when the village population increased through migration.

RSLR experienced in village houses

We used structured interviews to investigate community adaptation to increased flood frequency and inundation along the 20 km coastline gradient between Semarang and the Wulan Delta. In total, 194 households, distributed over 14 villages along the coast participated in the interviews, which were conducted by a group of students and local volunteers who spoke the local language. Respondents were asked in what year their house was constructed, and how much they had raised the ground floor of their house over the years. In addition, they were asked to indicate what the original height of the gutter had been when their house was constructed. The current gutter height was then measured in situ by the volunteer who conducted the interview. The difference between the original gutter height and the current gutter height indicated how much the house had 'sunk' relative to the water level over time, because, in many cases, the inhabitants only invested in raising the floor of their house; they did not adjust the walls or roof of their house. Over time, the gutter of a house moves closer to the street level, as streets are also heightened regularly to deal with frequent flooding[30]. The RSLR rate experienced by the house was then calculated using the floor raising data and the gutter data with the following formulas:

$$\text{RSLR at house (floor)} = \frac{\text{total amount the floor was raised since construction (cm)}}{2020 - \text{construction year}}$$

$$\text{RSLR at house (gutter)} = \frac{\text{gutter height at construction (cm)} - \text{current gutter height (cm)}}{(2020 - \text{construction year})}$$

The outcome of the two experienced RSLR calculations was validated against each other, rendering a clear linear correlation with an R^2 of 0.5 (Extended Data Fig. 4). Five houses were omitted from the RSLR calculation because they had raised their walls after raising the floor or because they constructed an entirely new house where they already anticipated the flooding frequency and RSLR to come.

The gutter height data were then used to compare RSLR experienced in the village to RSLR experienced by the mangroves (for methods, see next paragraph). To this end, an average experienced RSLR rate (±95% CI) was calculated from the gutter dataset for each of the villages located directly along the shore (notably: 18 houses in Sriwulan at 0 km, 4 houses in Purwosari at 2.8 km, 6 houses in Bedono at 5.1 km, 12 houses in Timbulsloko at 6.5 km, 10 houses in Surodadi at 8.8 km, 10 houses in Tambakbulusan at 11.8 km, 10 houses in Morodemak at 13.8 km, 18 houses in Wedung at 19.3 km, 17 houses in Berahan Kulan at 21 km and 14 houses in Berahan Wetan at 23.3 km from Semarang). Distances were obtained using the line measurement tool in QGIS (version 2.18.12 and version 3.22.3) between the centroids of each of the village's administrative boundaries and the start of the mangrove RSLR gradient in North-East Semarang. Data were loaded into RStudio (V1.4.1106, 2021) using readr (v 1.4.0), and pre-processed and explored using naniar (v 0.6.0), tidyr (v 1.1.2), stringr (v 1.4.0) and ggplot2 (v 3.3.3). The relation between mean experienced RSLR of villages, mean experienced RSLR of mangroves (for methods, see next paragraph) and distance from the city was investigated with a log-linear model, using RStudio (V1.4.1106, 2021), package nlme (v 3.1-152). In this model, the response variable 'experienced RSLR rate' was log-transformed, and the site type 'village' or 'mangrove' was added as a factorial explanatory variable. Longshore distance, a numerical variable that contained the distance from tree or village of interest to start of the RSLR gradient, was added as a second explanatory variable of interest. Fitted curves from this log-linear model were plotted in Fig. 4a, on top of the observed average (±95% CI) experienced RSLR rates in villages and mangroves.

RSLR experienced by mangroves

RSLR experienced by mangrove forests along the expected rural RSLR gradient was quantified with the use of small pressure sensors (Onset HOBO Water level logger U20L-04), which were covered with a sock (to prevent theft) and tied to the trunks of two mangrove trees at each of the eight monitored mangrove stands located along 20 km of coastline. The loggers were configured using Hoboware Pro (v.3.7.12) to measure the pressure every 15 min, and were deployed for a period of 2.25 years. Due to the way in which the sensors were deployed (Extended Data Fig. 5a), all sensors were located well above mean sea level (MSL), ranging from 22 cm to 27 cm above MSL. These exact levels were determined in hindsight through comparison of the inundation curves of the loggers with the tidal constituents (methods explained in more detail below). The sensors were cleaned and redeployed repeatedly. Whenever a sensor tree was lost by a storm, a new sensor was deployed on a tree further inside the mangrove forest, anticipating future storms.

The regular loss of trees and sensors ultimately led to five continuous pressure datasets that ran for more than 1 year, from which RSLR experienced by mangrove trees could be quantified. To do so, the raw pressure files were first corrected for air pressure (obtained from the daily emerged window of each sensor), and then converted to water depth, assuming a constant temperature of 30 °C, and a salinity of 30 ppt, which is the average year-round temperature and salinity for this region. Resulting water depth time series were then fitted to the subsidence-corrected tide prediction, which was obtained through a tidal harmonic analysis of freely available data from the tide station in Semarang (see 'Subsidence of the tide monitoring station in Semarang'). The exact height of the logger with respect to MSL was determined by comparing submergence time per day of the loggers, averaged over the first 3 months, to expected submergence time based on the stations' tidal signal (Extended Data Fig. 6). This 90 day period was long enough to average out weather effects, but short enough not to be affected by RSLR. After fitting of the logger's water level series to the tidal curve, inundation time and average water depth recorded by the loggers could then be corrected for expected inundation time and average water depth based on the position of the logger in the intertidal zone at the start of the monitoring period. Unfortunately, a linear regression through all water level logger points per logger over the full deployment time of each logger was not possible, because multiple loggers were deployed near a creek or river mouth. We observed a substantial increase in water level over the wet season for those loggers, clearly caused by freshwater run-off during the wet season. We could not correct for this effect because the discharge of each of the individual rivers and creeks was unknown. We therefore excluded the data from the wet season, and only used tide-corrected water levels during the dry seasons. The average daily rainfall (downloaded from Semarang's weather station, https://dataonline.bmkg.go.id/) was generally low during these monitored windows in the dry seasons of 2018 and 2019 (1.2 mm per day and 0.9 mm per day, respectively), and a Kruskal–Wallis rank sum test over a total of 364 days did not reveal a significant difference in average daily rainfall between the 2 years ($X^2 = 3.2$, d.f. 1, $P = 0.8$). This leads us to assume that rainfall had little influence on the tide-corrected water levels measured between those years. Differences in average tide-corrected water depths between the two dry seasons were tested with a two-sided independent *t*-test for each site. The resulting mean difference (±95% CI) in water depth between two consecutive dry seasons (a period of 60 days, exactly 1 year apart) was then used to calculate experienced RSLR rates by mangroves (Extended Data Fig. 6).

$$\text{RSLR experienced by mangroves} = \frac{\text{tide corrected waterdepth 2019} - \text{tide corrected waterdepth 2018}}{1\ \text{year}}$$

The site at 5.3 km from the subsidence epicentre had an overlapping period of only 15 days, instead of 60 days between the 2 years, because the tree with the longest deployed logger was lost shortly after re-deployment of the logger. Due to the critical location of this datapoint with respect to the assumed subsidence gradient, we decided to include the resulting mean RSLR rate of this site for further analyses despite its wider CI (Fig. 4a), but we validated if the RSLR trend along the coastline would be similar if only the 15 day period would be used for all sites, which was indeed the case, although CIs became wider

(Extended Data Fig. 7a versus Extended Data Fig. 7b). In addition, we used the four sensors along the gradient that had longer time series to do two extra validations with 60 days time series later in the dry season (June–August (Extended Data Fig. 7c) and August–October (Extended Data Fig. 7d)). All time series showed similar trends in RSLR and increased daily submergence time along the coastline. The clear spatial trend in RLSR suggest that an important component of the RSLR that we measured was related to subsidence in the city that propagated to the adjacent rural area. It should be noted that loggers should be deployed over longer time scales to also include longer-term processes, such as El Niño–Southern Oscillation (ENSO) and their contribution to average experienced RSLR. During El Niño years, ENSO can cause a drop in sea level in the West Pacific, and lower precipitation. The loggers in this study were deployed during 2018–2019, which was a mild El Niño year, whereas the preceding year (2017–2018) was a mild La Niña year (National Oceanic and Atmospheric Administration[52]). This could also partly explain why the logger at the site 20 km from the subsiding city showed a net drop in sea level during the measured year. Assuming that all sites along the coast have experienced the potential decrease in sea level with the mild El Niño in 2018–2019 similarly, our estimates for RSLR for this mangrove coast would be conservative compared to longer-term averages. Nonetheless, ENSO or other regional to global, longer-term processes, cannot explain the extent of spatial variation observed in our data. Combined with all the other datasets presented in this study, we argue that this decreasing RSLR with increasing distance from Semarang can be linked to local subsidence.

Bare foreshore dynamics

To monitor foreshore dynamics on the bare foreshore seaward of mangrove stands, two polyvinyl chloride (PVC) sediment monitoring poles were placed at approximately 50 m seaward of each RSLR-monitored mangrove stand (Extended Data Fig. 5b). Each pipe had a diameter of 10 cm and was 2 m long. The poles were marked at every 10 cm with tape and driven 1 m deep into the sediment. We monitored the depth of the foreshore, and the relative bed-level change at each pole three times over a period of 2 years. At locations where scour had occurred around the base of the pole, we used a spirit level to bridge the distance across the scour hole (±20 cm) to measure the level of the undisturbed bed with respect to the markings on the pole. Water depth measured at the sedimentation pole was corrected to depth compared with MSL, using predicted tide ('Subsidence of the tide monitoring station in Semarang') at the time of water level measurement each field visit.

After the whole monitoring period for each site, only one of the two monitoring poles could be recovered at all sites. At the two most eroding sites (0 and 3.3 km from Semarang), the erosion rates were so high that the PVC poles were lost within the first 8 months of deployment. The depth of the original pole location had become too deep (subtidal) for deployment and monitoring of a new PVC pipe. Monitoring of a subtidal pole was unfeasible, as relocating a submerged PVC pipe with Global Positioning System during follow-up visits was difficult due to the turbid water, and we could not use marker buoys to mark a submerged monitoring pole as previous experience made it clear that those would probably be lost between visits. The new location therefore had to be more shallow than the original location, and the most meaningful choice was therefore to place the new pole 50 m out of the retreated mangrove fringe. The placement of the two new poles at a more shallow location meant that for these two sites there was no continuous bed-level dataset, which would have contained increasingly deeper bed levels. The foreshore depth data that are displayed in Fig. 4b therefore represent a conservative average foreshore depth at subsiding sites. The loss of the original monitoring poles at these two sites, also meant the absence of bed-level change measurements for those sites. We therefore assumed a conservative 60 cm of vertical erosion compared to baseline between the first two field visits. This amount of erosion would have toppled over the pole with its original 1 m anchoring depth, and it appeared to be a conservative estimate based on the observed depth at the original locations of these two poles 8 months after initial deployment.

The bed-level change rate between each field visit was recalculated to a mean sedimentation/erosion rate per month by dividing bed level change between field visits by the number of months between the visits. We then used all available relative bed-level change rates measured per site to obtain a mean and 95% CI of foreshore bed-level change per year. Correlation between foreshore depth and experienced RSLR measured in the nearby mangroves, and the relation between foreshore erosion and foreshore depth were tested with linear regression models, using each depth measurement ($n = 4$) at t_n and subsequent bed level change rate between t_n and $t_n + 1$ ($n = 3$)) as replicates to include temporal variability. We excluded the site 10 km from Semarang from the analysis, as that sedimentation pole was repeatedly removed by people. The sites at 12.5 km and 20.1 km from Semarang were added later to the monitoring gradient and therefore only had three replicates in time for depth and two replicates for bed-level change.

Mangrove response to experienced RSLR

To monitor morphological responses of mangrove trees to experienced RSLR, we marked ten pneumatophores on trees at monitored sites along the RSLR gradient. A cable tie was tied to each pneumatophore at 10 cm from the tip, and at 10 cm from the bed, to quantify changes in root growth and bed level (relative to the tree) respectively (Extended Data Fig. 5c). Cable ties are an easy method to monitor pneumatophore growth, as they are durable in the rough field conditions and do not interfere with the extension of the pneumatophore[53]. Due to substantial lateral loss of marked trees after the first monitoring period, we selected three or four additional trees per site (including the trees with a water level logger) and monitored those trees two more times for bed-level change and root growth over the period of the following 1.5 years.

Bed-level monitoring in mangroves

Bed-level change relative to mangrove trees (presented in Fig. 4d) was monitored by measuring the distance from the bed to the cable tie that was fastened 10 cm from the bed at baseline. Net forest floor accretion rates were subsequently calculated by dividing the bed-level change by the time that had elapsed between the monitoring period and baseline. Due to lateral loss of monitoring trees and damage to remaining marked pneumatophores in the second year of monitoring, only the mangrove response data of the first 8 months were used to compare the vertical bed-level changes in the mangrove fringe between sites along the coast. The relation between within mangrove accretion rates and foreshore depth was of particular interest (due to the potential sediment source for accretion), and was tested with a linear mixed effects model using RStudio (v1.4.1106, 2021) and package MASS (v 7.3 - 53). Bed-level change rate (cm per month) was used as a response variable ($n_{pneus} = 162$) with tree as a random effect as pneumatophores were nested per tree ($n_{tree} = 22$), and using foreshore depth as an explanatory variable.

Aerial root-growth monitoring

Pneumatophore growth (presented in Fig. 4e) was monitored by measuring the length of each marked pneumatophore from the tip to the cable tie upon each visit to the site. Pneumatophore growth rate was subsequently calculated from the measured root-tip extension, divided by the time elapsed since baseline. While we visited all sites at 7 months and 19 months after baseline, we decided only to use the mangrove response data between t0 and t7, as lateral tree loss and pneumatophore damage over the consecutive monitoring year (between t7 and t19) made the cable tie to tip measurements less representative of pneumatophore growth. The effect of experienced RSLR on pneumatophore growth was tested at the sites where bed-level change inside the

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fringe was negative or zero over the period of the study (Fig. 4d, sites >5 km from Semarang). To investigate the effect of RSLR experienced by mangrove trees on pneumatophore growth under limited accretion, we performed a linear mixed effects model, using experienced RSLR as an explanatory variable (fixed factor) and tree as a random effect, because pneumatophores were nested per tree. Sites that we did not have RSLR data for were excluded from the analysis, resulting in 85 observations of pneumatophore growth nested within 12 trees.

Root-mat quantity assessment tree

The number of rootmats that a tree had grown over its lifetime was quantified (presented in Fig. 4e) to investigate how mangrove trees responded to ongoing RSLR over the past decades, we rinsed out the root zones of three living mangrove trees with a 60 m^3 h^{-1} motorized water pump at three key sites (n = 3 per site): (1) a site with high experienced RSLR, high sedimentation rates in the fringe, and young trees (0 km from Semarang); (2) a site with high experienced RSLR, high sedimentation rates in the forest, and old trees (3.3 km from Semarang); and (3) a site with low experienced RSLR, low sedimentation rates in the forest, and young trees (20 km from Semarang). At each site, the number of distinctly separate root mats per tree (Extended Data Fig. 5d) was quantified in the top 60 cm of the sediment; deeper excavation and rinsing was not possible. A root mat was defined as a distinct level at the tree stem, where a clear large number of cable roots protruded from all sides of the tree (thus forming a layer), which was surrounded above and below by areas without cable roots coming from the stem (Extended Data Figs. 3 and 5). To test the relation between the number of root mats and experienced RSLR rate of the forest, we had to substitute the missing datapoint in RSLR for the site at 3.3 km from Semarang. As the loggers were lost every wet season, we were unable to measure the continuous RSLR rate at this site. The strong correlation between the (log transformed) measured RSLR rates and distance from Semarang (R^2 = 0.94 and P < 0.01), however, allowed for substitution of this value through log-linear regression. We were then able to test the effect of experienced RSLR on root mat formation over these three sites, using a generalized linear model, assuming a Poisson distribution for the root mat counts and using the experienced RSLR rate for each site as an explanatory variable. This model was slightly underdispersed, so to validate the outcomes we also tested whether the differences observed in the number of root mats between the sites were statistically significant with a Kruskal–Wallis test.

Experiment examining mangrove resilience to sudden sedimentation

The effects of extremely high sedimentation pulses were simulated in the field by exposing saplings (height 60 cm, n = 6 per treatment group) and young trees with pneumatophores (height 2 m, n = 4 per treatment group) to a sediment increase of either 20 cm or 40 cm, with a control group where no sediment was added. A PVC tube (diameter 30 cm) was put over the saplings and filled with locally available sediment. The young trees were surrounded by fencing, constructed from bamboo and plastic and filled with sediment. Sapling survival was assessed after 22 days at the end of that field visit, young tree survival was assessed after 60 days, at the start of the next field visit. Survival in each treatment was tested against an expected natural survival rate of 90% with a binomial test (Extended Data Fig. 2). Unfortunately, we did not quantify any root-morphological changes during this experiment, as that was not yet our focus at the time.

Lateral mangrove erosion

Lateral mangrove erosion (presented in Fig. 4c) was quantified by counting the number of dead trees seaward of the mangrove fringe per 50 m coastline stretch at each of the sites along the coast in the RSLR gradient. Each site was approached by boat at low tide so that the dead trees on the bare foreshore were visible. To get a general overview of the state of the mangrove fringe at the respective location, the number of dead trees within a 50 m stretch was counted alongshore, starting several metres from the boat. Thereby a 50 m tape measure was fixed (either on a tree or held), while one person walked along the coast counting the number of (visual) dead trees until the tape would reach its end. Fallen as well as standing trees were counted. In addition, loss of monitored pneumatophores gave a clear indication of lateral erosion as well, as marked pneumatophores were often distributed around the tree, so 50% mortality of marked pneumatophores was often a result of lateral erosion in the field, which left the monitored tree at the seaward edge of the mangrove forest. Pneumatophore survival per site was monitored two times in 1.5 years, average survival per site and 95% CIs were plotted in (Fig. 4c). The effect of foreshore depth on pneumatophore mortality and number of trees per coastline stretch was tested with two separate generalized linear models. (1) For the dead tree data, which were counts, we assumed a negative binomial distribution in the generalized linear model, and used mean foreshore depth over the entire monitoring period as the explanatory variable of interest. (2) For the pneumatophore mortality data, we used the same explanatory variable, but for this model we assumed a binomial distribution in the response variable, as the marked pneumatophores were either dead (1) or alive (0) after 19 months.

Subsidence of the tide monitoring station in Semarang

Tidal harmonic analysis of data obtained from the water level monitoring station in Semarang[54] was performed to account for the tidal signal in the logger data. Using Matlab (version R2022b) with the UTide (v1p0) toolbox[55] on a water level time series between May 2016 and the end of 2018, amplitude and phase lag of each tidal constituent were determined. Besides expected tidal constituents, the tidal analysis also yielded a linear slope in the water level of 3.9 cm per year. Another sensor showed a linear trend of 7.9 cm per year before 2016, and a slope of 0.8 cm per year after the data gap in 2016 (Extended Data Fig. 8). The lack of data for several months and the lower slope of this linear component after the data gap suggest that the tidal station has been re-anchored at a deeper subsurface layer. Although we have not been able to obtain information about what has happened to this tidal station, the data show that even the deeply anchored structure experiences substantial subsidence. To use tidal data from the tide station for tide corrections of the water level loggers, we omitted the linear component from the model, resulting in a predicted tidal signal without the effect of subsidence. Subsidence of the tidal station barely impacts tidal analysis, as analysis of a time series before re-anchoring of the monitoring station yields very similar amplitudes and phase lags for each constituent.

Sediment deficit calculation for Semarang

Historic data that report coastline progradation (seaward expansion of the coastline) along the Demak coast were used to estimate the original sediment supply to the system. Recent data, documented on drawn maps from 1908 and 1937, show coastline progradation East of Semarang City[56]. The coastline there expanded with 265 m between these years (1908–1937). If we assume that land subsidence around this time was still minimal, coastline progradation would have been approximately 9 m per year. Assuming coastal profile of 1/1,000, this means that the pre-subsidence sediment supply to the system would approximately have been 9 mm per year of vertical accretion.

Inclusion and ethics statement

The group of authors who present this paper represent an international collaboration between knowledge institutes in the Netherlands and Indonesia. There are three Indonesian nationals involved as co-authors, representing different institutions and their science-policy networks in Indonesia (UNDIP Semarang, UGM Yogyakarta, national to local governmental agencies). The Indonesian researchers involved as co-authors brought previous knowledge from research results to the study and have involved other local researchers and students in the research process for capacity building. Results and new findings from this study have been shared regularly with local communities, managers and government throughout the duration of the project. Data and results were shared at local universities and community gatherings and through half-yearly knowledge exchange sessions with the ongoing coastline restoration project in the Demak region (https://indonesia.un.org/en/212655-un-recognizes-indonesian-effort-restore-mangrove-forests-special-award) in which Indonesian local, regional and national governments were also involved. One of the datasets in support of this manuscript was collected with the use of structured interviews among households throughout the research area to obtain technical data on house adaptations. No ethics committee was consulted for this study, as the focus of the study lay on the technical aspects of houses and not on the human population. Nevertheless, we did follow the ethical procedure of Utrecht University (consent, respect and no harm) when conducting the structured interviews, mainly focusing on the total amount of floor raised over the years to keep floods out of the house. Village heads of selected villages were notified of our initiative to collect house subsidence data and our intention to interview village inhabitants to collect those data; we proceeded with the interviews only after permission from both the respective village head and the participant was obtained. Potential participants were informed about the purpose of the study and asked if they wanted to participate. Interviewers also sought consent from participants to record their responses and take photographs of the homes for data processing. Participants were informed that their personal data would remain anonymous and stored in password-protected computers, but that a map of the experienced sea level rise based on the houses' data would be made available. Respondents did not receive payment or compensation for participating in the interviews. All approached households were positive towards participation in interviews to obtain the technical data of house adaptations to RSLR and publication of the results.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data in support of this manuscript can be found at https://doi.org/10.4121/22096397. The village census data from which migration fluxes were derived were obtained from the website of the central bureau of statistics of Demak Regency, available at https://demakkab.bps.go.id/publication.html. Rainfall data were downloaded from Semarang's weather station (https://dataonline.bmkg.go.id/). Finally, data from the tide monitoring station in Semarang were obtained from http://www.ioc-sealevelmonitoring.org/station.php?code=sema.

Code availability

Relevant code in support of this manuscript can be found at https://doi.org/10.4121/22096397.

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Author contributions

All authors contributed to the work presented in this paper. C.E.J.v.B. designed experiments, supervised students (S.R., T.S.H. and C.v.S.), did the formal analysis and wrote the initial draft of the paper. T.J.B. conceived the idea and drew the overarching study design. P.M.J.H. and B.K.v.W. both had valuable contributions to interpretation of the results and conceptualization of their meaning on a larger scale. Both authors also contributed proactively to the storyline of the manuscript. S.R. co-designed and remotely coordinated interviews on effects of RSLR in the villages, which included the floor raising data. S.R. also contributed to formatting of conceptual Figs. 1 and 5. T.S.H. co-designed and conducted sedimentation experiments in the field. C.v.S. co-designed and conducted the mangrove root mat field survey. S.A.J.T. contributed substantially to the analysis of the mangrove experienced RSLR data. A.T., M.H. and F.H.T. provided valuable insights into the socio-economic context (A.T.) and the historical subsidence of the region (M.H.) and facilitated our research through their networks (A.T., M.H. and F.H.T.). All authors reviewed the manuscript multiple times.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41893-023-01226-1.

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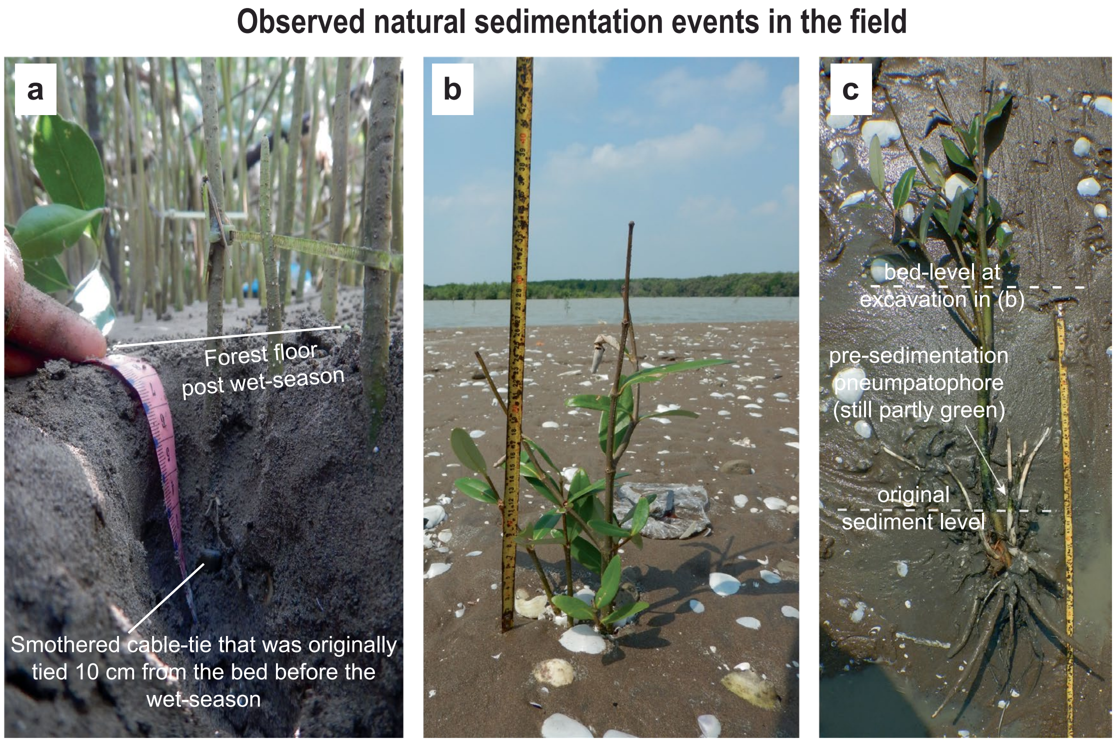
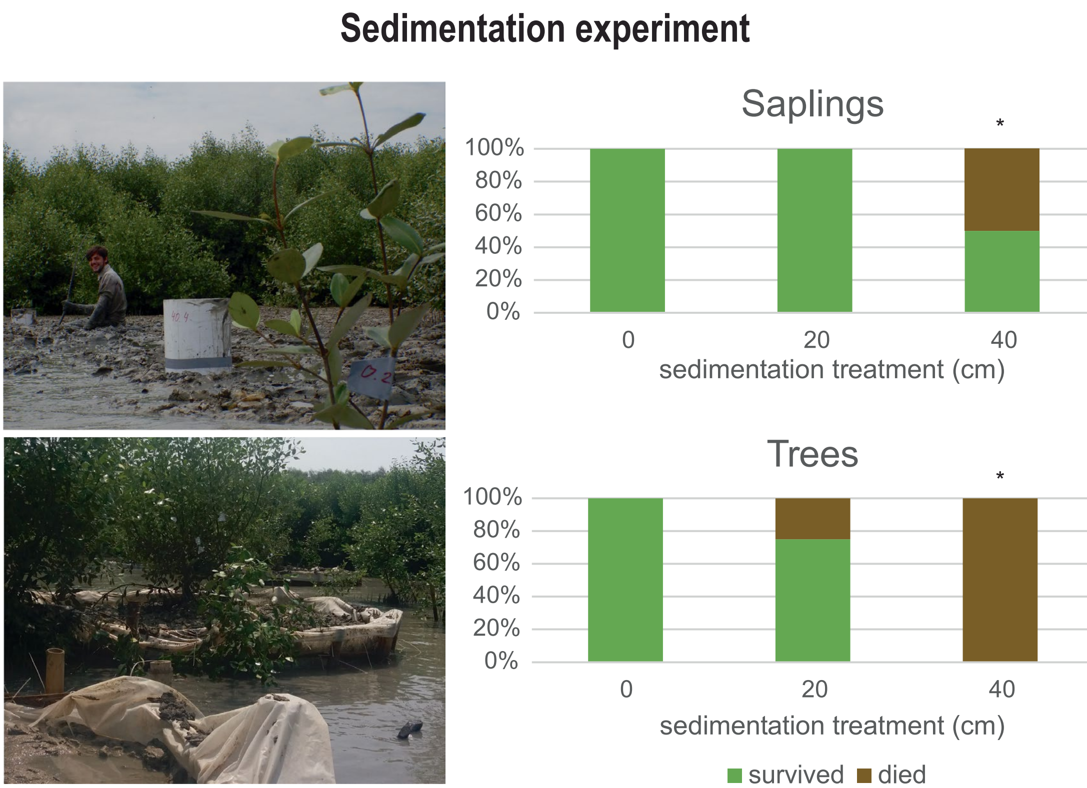


Extended Data Fig. 1 | Observed natural sedimentation events in the field. Field observations of sedimentation events over short periods of time. **a**. One of the monitored sites where cable-ties had been used to mark pneumatophores 10 cm from the tip and 10 cm from the bed before the wet-season. This picture, taken a few months later shows that the site had been subjected to substantial sediment deposition that buried the lower cable tie under several centimetres of sediment. **b**. A mangrove sapling on the landward edge of a chenier (sand lens on top of a mudflat), seaward of the mature mangrove fringe. The green pneumatophore part that is revealed after excavation of the sapling (**c**) used to be exposed to sunlight and suggest that this sapling recently encountered a sedimentation event of roughly 30 centimetres, after which pneumatophores started to extend (white pneumatophores and pneumatophore parts). Photos: Celine van Bijsterveldt.



Extended Data Fig. 2 | Sedimentation experiment. Saplings and young mangrove trees with pneumatophores can survive sedimentation events of 20 cm per event. 40 cm of sudden sedimentation caused survival rates that were significantly lower than the expected survival of 90% * in both saplings and young trees. Photos: Celine van Bijsterveldt.

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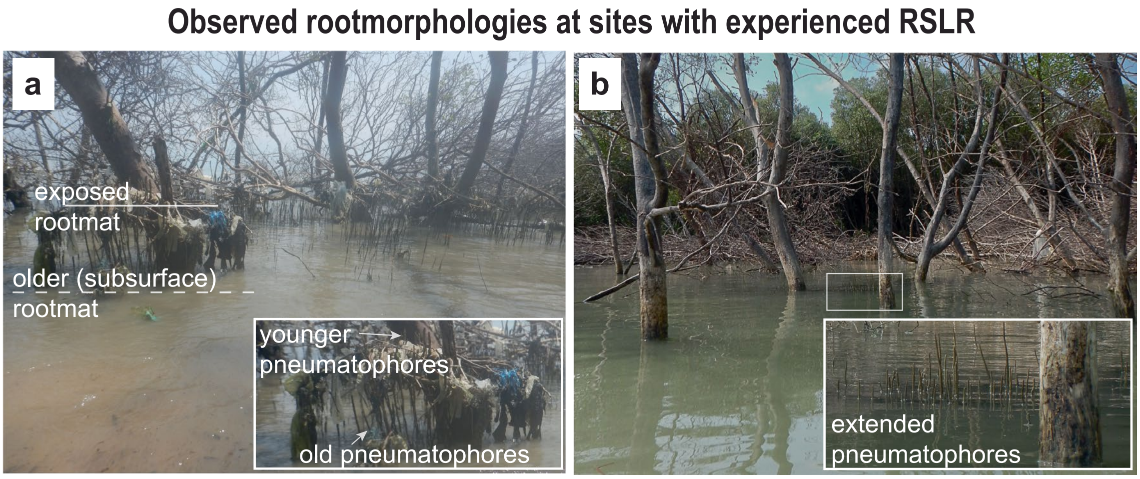

Extended Data Fig. 3 | Observed root morphologies at sites with experienced RSLR. Two mangrove fringes that are subjected to RSLR. The erosion reveals past morphological adaptations in the root-systems of mangrove trees at these sites experiencing rapid RSLR. **a**. A mangrove fringe that is subjected to rapid RSLR with evidence of multiple root mats per tree. This site has been subjected to RSLR, sudden sedimentation (during which the second rootmat developed) and was later hit by lateral erosion. During the sudden sedimentation, trees seemingly responded to the anoxia in their (now buried) original pneumatophores, by growing new pneumatophores from fresh cable roots in the top of the new sediment layer. The excess sediment has recently disappeared during erosion, revealing the secondary root mats and even some of the older pneumatophores, which are attached to an older subsurface root mat that now still anchors the tree. **b**. A mangrove fringe subjected to moderate RSLR where only erosion has occurred. These trees do not have multiple root mats, only extended pneumatophores to keep up with the rising water level. Photos: Celine van Bijsterveldt.

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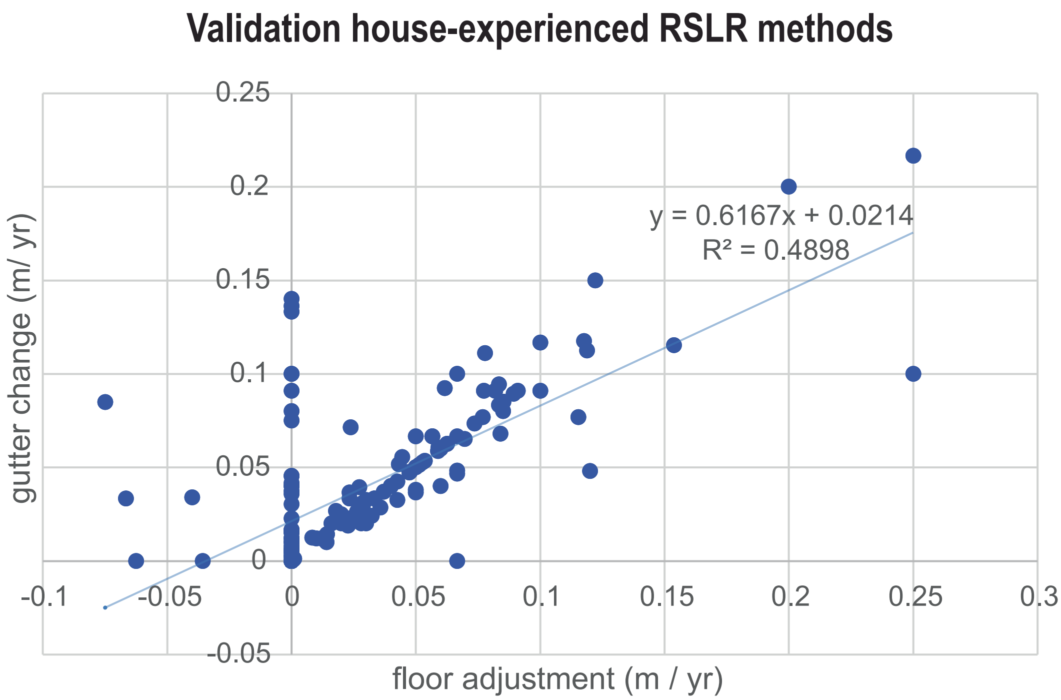

Extended Data Fig. 4 | Validation house-experience RSLR methods. Correlation between the two ways of calculating house experienced RSLR rates.

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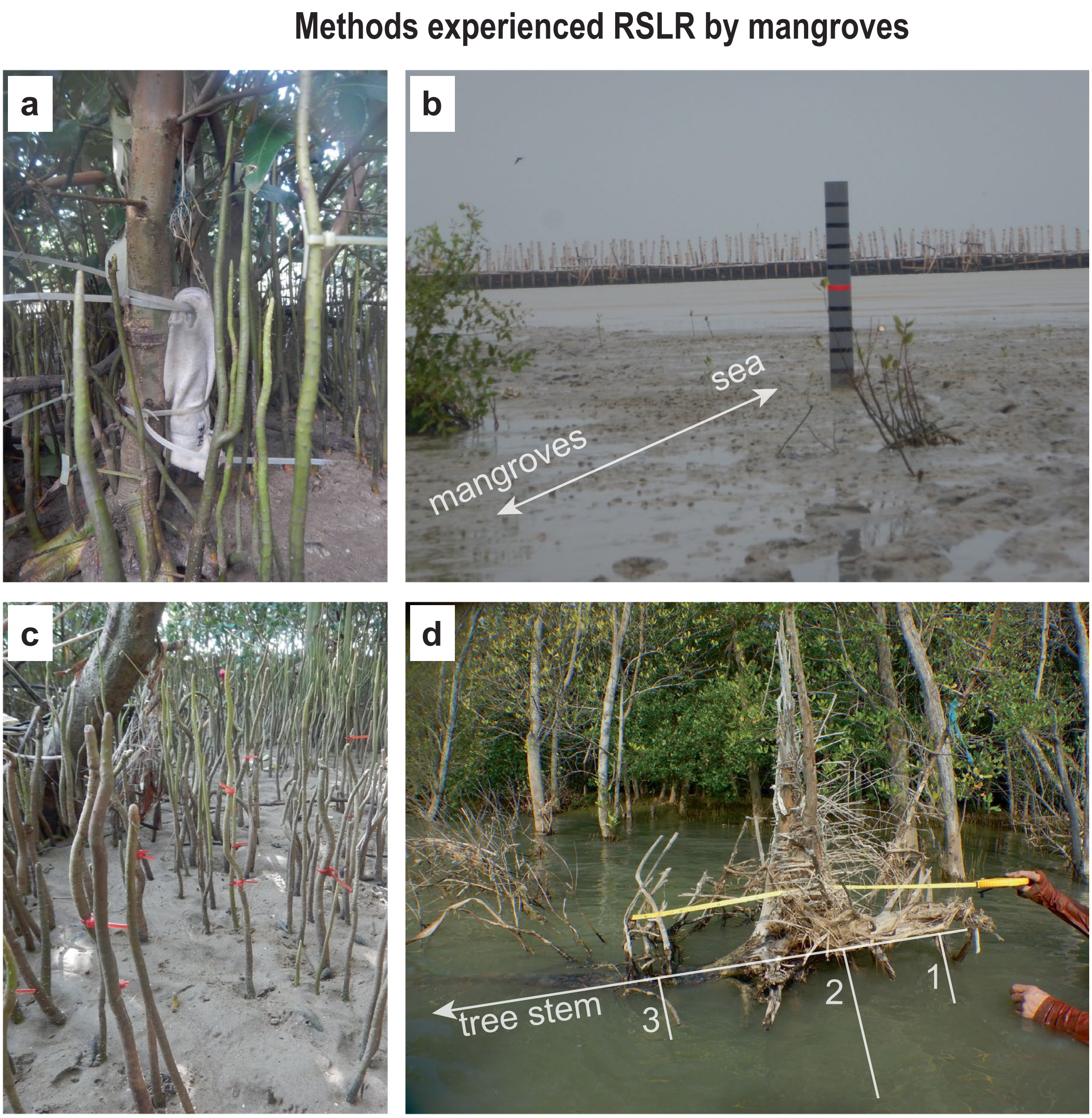

Extended Data Fig. 5 | Methods experienced RSLR by mangroves. Methods applied in the field to monitor effects of experienced RSLR by the mangrove fringe and the bare fore-shore. **a**. Camouflaged pressure sensor deployed on a young mangrove's tree trunk around 20 cm from the bed. **b**. Sedimentation pole approximately 50 meters seaward of the mangrove fringe. **c**. Pneumatophore markings in the form of small red cable-ties applied at 10 cm from each root's tip and 10 cm from the bed at baseline. **d**. Example of a dead mangrove tree (toppled over) with multiple distinguishable root-mats (oldest to youngest, 1 to 3). Photos: Celine van Bijsterveldt.

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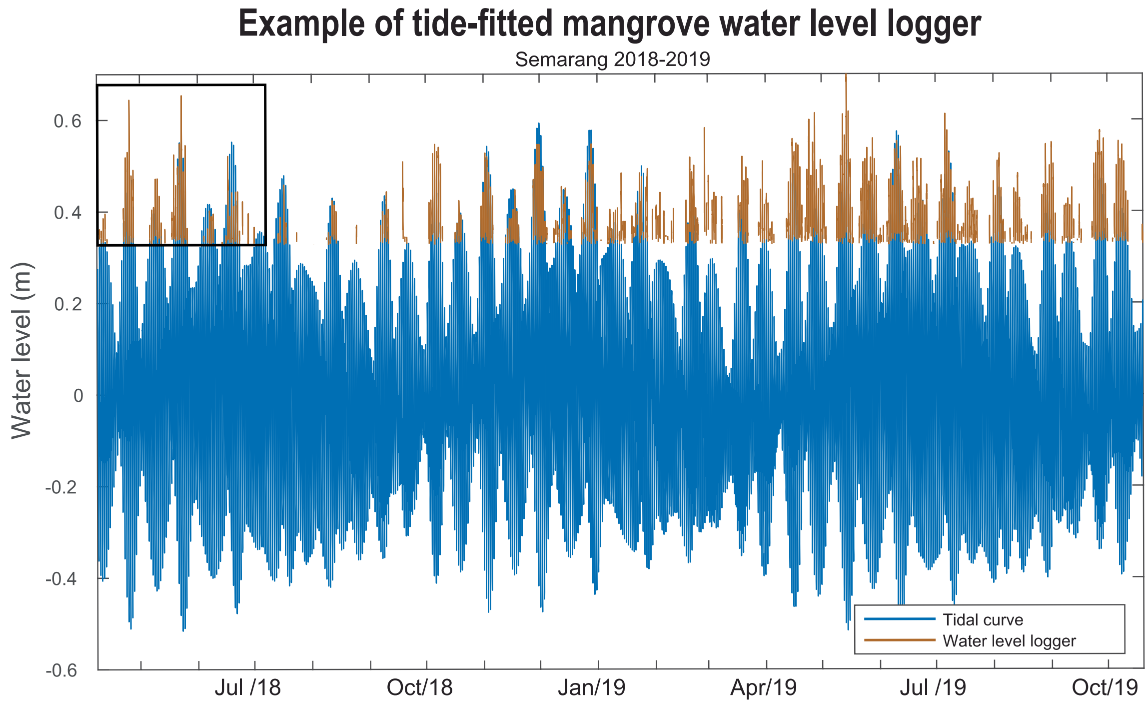

Extended Data Fig. 6 | Example of tide-fitted mangrove water level logger. Raw data of one of the water level loggers, fitted to the tidal curve derived from the tide station of Semarang harbour. The black box indicates the first three months that were used to fit the logger to the tidal curve using average daily inundation time. The subsidence of this station was determined using the average tide corrected mean water level per day measured by the logger during the timeframe indicated by the blue line below the x-axis in 2019 with the same period (blue line) in 2018. To validate this trend, the same was done for a timeframe during the mid-dry season (green line below the x-axis) and the late dry season (red line below the x-axis). Wet season data were thus not used for the analysis to exclude the influence of rainfall and run-off on water level change.

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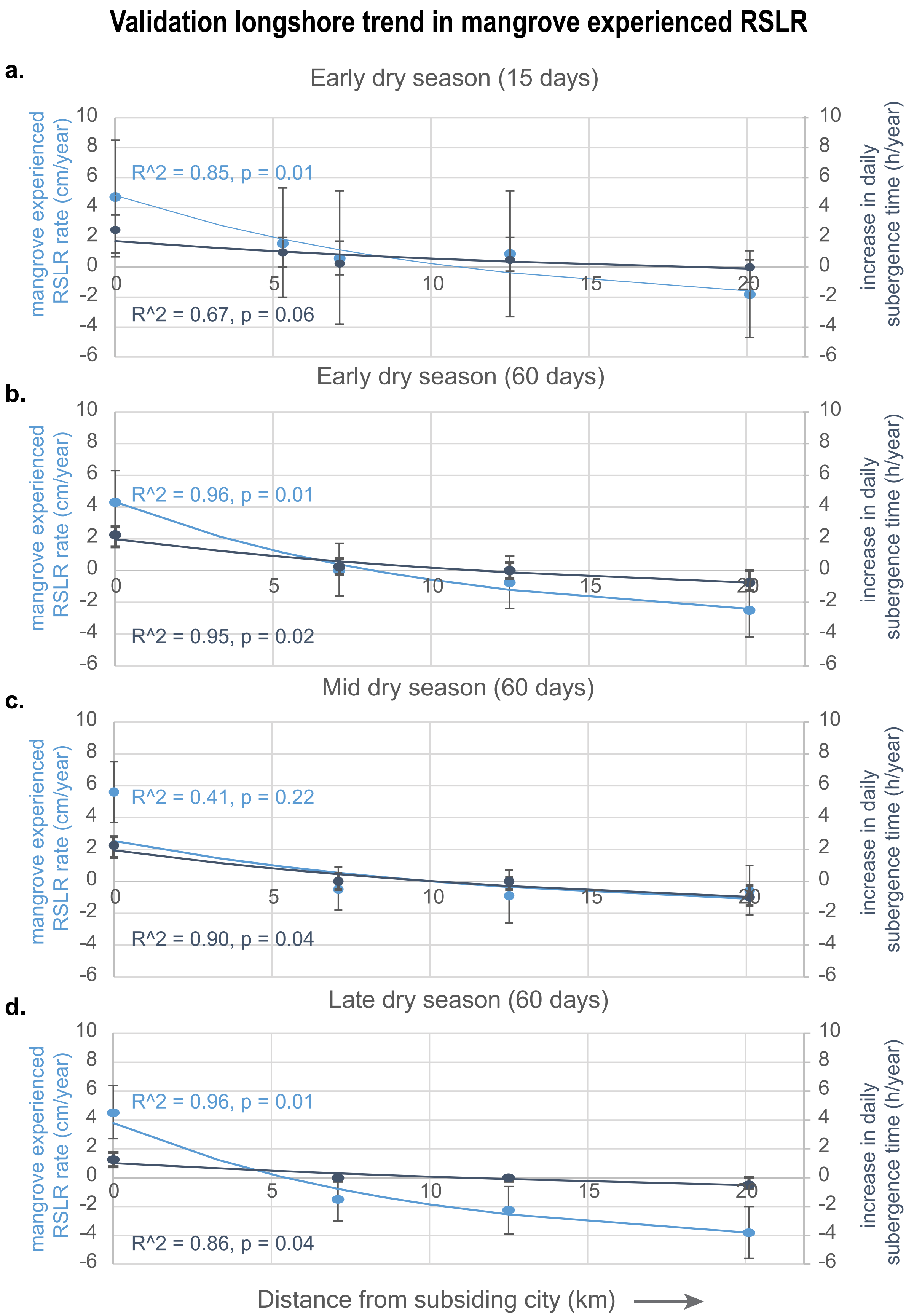

Extended Data Fig. 7 | Validation longshore trend in mangrove experienced RSLR. Validation of mangrove experienced RSLR rates along the subsidence gradient, using different dry-season time windows (n = 15 days for the upper panel (a), and n = 60 days for the other three panels (b–d)) to obtain mean (+/− 95% confidence intervals) water level change between 2019 and 2018 through two-sided t-tests for each site. R^2 and p-values per panel indicate the significance of the relation between mean water level change and distance from subsiding city, based on log-linear regression. Note: the x-axis title in the lower panel applies to all panels.

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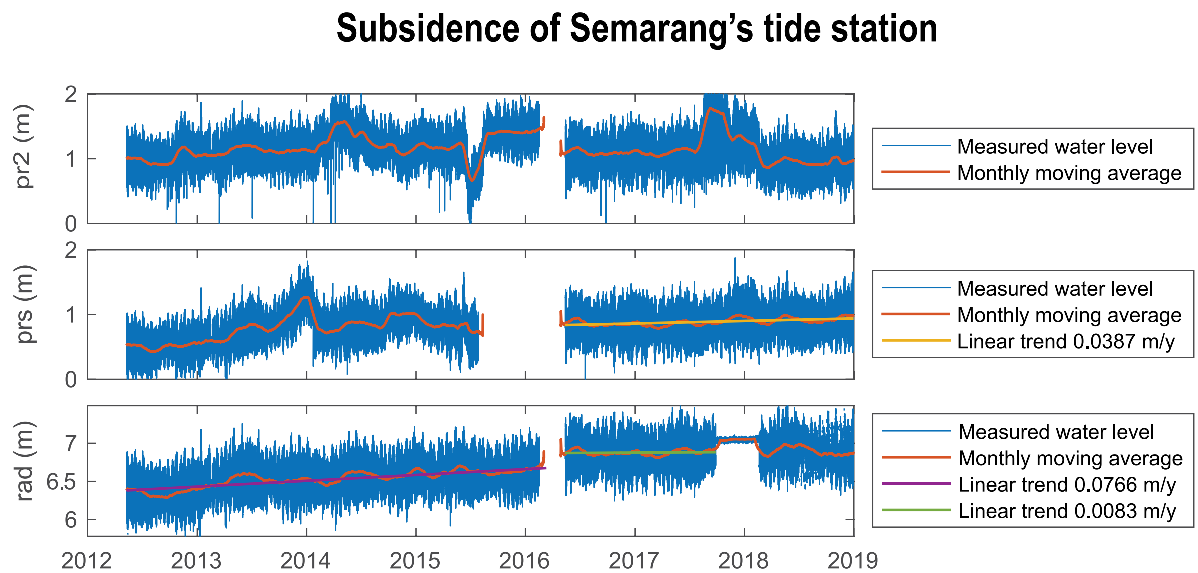

Extended Data Fig. 8 | Subsidence of Semarang's tide station. Water levels as measured by the three sensors (two pressure sensors (prs & pr2), and a radar (rad)) of Semarang's tide station. The radar signal shows a linear increase in water level of 8 cm per year before the data gap in 2016. After the data gap the linear increase in water level has decreased to 8 mm per year. It is unclear what has happened during the data gap, but it seems plausible that the station was anchored at a deeper sediment layer.

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Hoboware Pro (v.3.7.12) was used to configure the water level loggers and read out the data, and convert to .csv files from the loggers after deployment.
Data analysis	Google Earth Pro (version 7.3.3.7786) was used for a timeline search to identify major erosion events near Semarang. QGIS (version 2.18.12 & version 3.22.3) was used to visualize spatial distribution of relevant data: Village level population census data (migration fluxes and population density) and the house subsidence data (collected on the ground). For data-processing of the water level logger data to obtain mangrove subsidence rates, we used Matlab version R2022b with the UTide v1p0 toolbox. For statistical analysis in this paper we used RStudio (V1.4.1106, 2021) with packages: readr (v 1.4.0), naniar (v 0.6.0), tidyr (v 1.1.2), stringr (v 1.4.0), ggplot2 (v 3.3.3) for data preparation and exploration. In addition we used the packages: nlme (v 3.1-152) and MASS (v 7.3 - 53) for the linear mixed effects models. Code in support of the analyses in this manuscript can be found at: 10.4121/22096397.

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All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

Data in support of this manuscript can be found at doi: 10.4121/22096397. Rainfall data were downloaded from Semarang's weather station https://dataonline.bmkg.go.id/ . Data from the tide monitoring station in Semarang were obtained from: http://www.ioc-sealevelmonitoring.org/station.php?code=sema The village migration data were obtained from the website of the central bureau of statistics of Demak Regency, available at: https://demakkab.bps.go.id/publication.html. Through here publications of census data per subdistrict of interest are available (our villages of interest lie withing the subdistricts of Bonang, Karang Tengah, Sayung and Wedung) . Links to the specific reports of these subdistricts that were availabe are: https://demakkab.bps.go.id/publication/2012/02/24/e816848ca2e7d0f75aae127a/kecamatan-sayung-dalam-angka-2009, https://demakkab.bps.go.id/publication/2012/02/24/ab712ab410f361661341889c/kecamatan-sayung-dalam-angka-2011, https://demakkab.bps.go.id/publication/2015/11/02/a34138b80868ea12ef849188/kecamatan-sayung-dalam-angka-2015, https://demakkab.bps.go.id/publication/2020/09/28/e2b68b66d1bd4a11d717b1b2/kecamatan-sayung-dalam-angka-2020.html, https://demakkab.bps.go.id/publication/2012/02/24/dcbab44d28c93a40a52ce1d4/kecamatan-wedung-dalam-angka-2009, https://demakkab.bps.go.id/publication/2012/02/24/8cf461e906bccf6bf5fd1f44/kecamatan-wedung-dalam-angka-2011, https://demakkab.bps.go.id/publication/2015/11/03/e784fc76eae10c6b188c280e/kecamatan-wedung-dalam-angka-2015, https://demakkab.bps.go.id/publication/2012/02/24/89ebe282425f1bf2aba74149/kecamatan-karang-tengah-dalam-angka-2011, https://demakkab.bps.go.id/publication/2015/11/02/364c8c5d2beedbb29b92f569/kecamatan-karangtengah-dalam-angka-2015, https://demakkab.bps.go.id/publication/2020/09/28/be17807658d2ea6b7a87fd92/kecamatan-karang-tengah-dalam-angka-2020.html, https://demakkab.bps.go.id/publication/2012/02/24/6f78345164ed2e8aa41fdccb/kecamatan-bonang-dalam-angka-2011.html, https://demakkab.bps.go.id/publication/2015/11/02/e6456add49747801851b06ad/kecamatan-bonang-dalam-angka-2015.html, https://demakkab.bps.go.id/publication/2020/09/28/6b1e5bacd3eea5bb2cf93af6/kecamatan-bonang-dalam-angka-2020.html

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	For one of the datasets in this manuscript people were interviewed about parameters related to subsidence of their house (the year in which it was constructed, how often the ground floor had been raised since then, and the height of the gutter at construction). The gender of the respondents is not reported in this manuscript, as we deemed that unrelated to the house-sinking parameters presented in this paper. The house-subsidence dataset that will be made available in support of this paper has been entirely anonymized and only contains the village in which the house was located, gutter height, floor raising data and house construction year, no other details about the house or the respondents will be disclosed.
Population characteristics	not applicable, see above
Recruitment	A group of students and volunteers were coordinated remotely (due to covid) to conduct the questionnaire based interviews with villagers. They visited all villages within the coastal zone of the 20 km studyarea. After permission from the village head, students entered the village to look for houses that were old (because new houses had not yet experienced RSLR and could therefore not be used as proxy for RSLR). If people were at home, they requested an audience with them, explained the purpose of the research and asked if they were willing to participate in the survey.
Ethics oversight	One of the datasets in support of this manuscript was collected with the use of structured interviews among households throughout the research area to obtain technical data on house adaptations. No ethics committee was consulted for this study, as the focus of the study lay on the technical aspects of houses and not on the human population. Nevertheless, we did follow the ethical procedure of Utrecht University (consent, respect, no harm) when conducting the structured interviews, mainly focusing on the total amount of floor raised over the years to keep floods out of the house. Village heads of selected villages were notified of our initiative to collect house subsidence data and our intention to interview village inhabitants to collect those data, we only proceeded with the interviews after permission from both the respective village head and the participant was obtained. Potential participants were informed about the purpose of the study and asked if they wanted to participate. Interviewers also sought consent from participants to record their responses and take photographs of the homes for data processing. Participants were informed that their personal data would remain anonymous and stored in password-protected computers, but that a map of the experienced sea level rise based on the houses' data would be made available. Respondents did not receive payment or compensation for participating in the interviews. All approached households were positive towards participation in interviews to obtain the technical data of house adaptations to RSLR and publication of the results.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description

To shed light on the future of low-lying rural areas in the face of sea level rise, we studied a 20 km long rural coastline neighbouring a sinking city in Indonesia (8 – 20 cm yr-1), hereafter called studyarea. Through the collection of data across 7 main topics, we show that villages experienced significant RSLR near the city. Mangroves also experienced RSLR near the city, although to a lesser degree, and were able to respond to RSLR rates 4.3 cm yr-1 through various root adaptations. The seven main investigated topics, and their respective datasets:

0. Village population migration
Response: migration flux (percentage of village population), based on census data (obtained from: https://demakkab.bps.go.id/publication.html)
Factor: coastline retreat
Sample size: entire population of all villages within study area

1. village house experienced RSLR:
response: experienced RSLR (cm / year) by household
factor: distance from subsidence epicentre (km)
sample size: 194 houses across 14 villages spread across the studyarea

2. mangrove experienced RSLR
response: RSLR experienced by mangroves (cm/year)
factor: distance from subsidence epicentre (km)
sample size: 5 trees spread across the 20 km studyarea
Each tree represents a continuous waterpressure dataset of which more than 15 days overlapped in the dry season between years to calculate mean (+/- 95% CI) water level increase at the mangrove tree stem.

2b. rainfall data
Response: daily rainfall (mm)
Factor: 2018 vs 2019
Sample size: 182 days in 2018, and 182 days in 2019

3. foreshore dynamics
response: bed-level change (cm/month) at 50 m seaward from mangrove edge
response: foreshore depth
factor: experienced RSLR (measured in mangroves)
sample size: 8 sites across the studyarea, monitored 3 times in 2 years' time

4. mangrove bed-level dynamics
response: bed-level change (cm/month)
factor: foreshore depth
sample size: Each of the 8 sites across the study area had 4 marked trees that had 10 pneumatophores marked at 10 cm from the bed (and 10 cm from the tip for pneu growth (see 5.). Alls 8 sites and trees were monitored 3 times over a period of 1.5 years. Due to loss of trees the sample size was reduced to 162 pneumatophores belonging to 22 trees after 8 months.

5. mangrove root acclimation
dataset 1: pneumatophore markings
response: pneumatophore extension (cm/month)
factor: experienced RSLR experienced by mangrove trees
sample size: Each of the 8 sites accross the study area had 4 marked trees that had 10 pneumatophores marked at 10 cm from the tip (and 10 cm from the bed (see 4.). Alls 8 sites and trees were monitored 3 times over a period of 1.5 years.

dataset 2: rootmat formation:
response: number of rootmats
factor: experienced RSLR experienced by mangrove trees
sample size: 9: 3 trees per site. 3 sites distributed across the study area, including the outer edges of the studyarea

dataset 3: sedimentation experiment:
response: young mangrove tree survival
response: mangrove sapling survival
factor: sedimentation (3 treatments: 0 cm, 20 cm and 40 cm of sudden sedimentation)
sample size: saplings 6 per treatment, young trees: 4 per treatment

6. lateral mangrove die-back
dataset 1: dead trees
response: number of dead trees per 50 m coastline stretch
factor: foreshore depth
sample size: 6 sites across the studyarea, including the outer edges of the study area

dataset 2: pneumatophore mortality

response: proportion of marked pneumatohpores dead after 19 months of monitoring
factor: foreshore depth
sample size: 40 marked pneumatophores of 4 trees, at each of the 8 sites across the study area.

Research sample

0. Village migration data
Village migration and population density data were obtained from the website of the central bureau of statistics of Demak Regency (Badan Pusat Statistik Kabupaten Demak. District in figures (Kecamatan Dalam Angka). Bonang, Karang Tengah, Sayung and Wedung (2021). Available at: https://demakkab.bps.go.id/publication.html. (Accessed: 21st May 2021)). The oldest census data available at village level were from 2009, with arrival and departure data per village available for every 5 years since then. Published shoreline change data, and a timeline search in Google Earth Pro (version 7.3.3.7786) for the area near Semarang showed that in 2009 a major shoreline change occurred, which would likely affect the livelihood of the local communities. We therefore decided to use the migration data at village level from 2009-2010 to investigate how many people moved away from the area after the event.

1. village experienced RSLR:
sample: 194 houses across 14 villages spread across the studyarea.
Description: old houses in villages of coastal demak, a low-lying aquaculture area on alluvial deposits: the older the house, the better it could be used to estimate RSLR rates (based on gutterheights and number of, and total amount of floor raisings over the years).

2. mangrove experienced RSLR
sample: mature mangrove trees in the coastal fringe spread across the studyarea
Genus: Avicennia spp.

2b. rainfall during dry seasons of RSLR measurements
Sample: 182 days in 2018 (2018-04-21 until 2018-10-19) and 182 days in 2019 (2019-04-21 until 2019-10-19) covering the early dry season to late dray season time periods used for the RSLR rate calculation and validation in mangroves.

Description: To be able to report the average (+/- 95% CI) daily rainfall during the two dry seasons that were used for RSLR measurements in mangroves and test if rainfall differed between the two years, we download daily measured rainfall data from a meteorological station near Semarang airport (https://dataonline.bmkg.go.id/).

3. foreshore dynamics
Per site, one PVC sediment monitoring pole at approximately 50 m seaward of each experienced RSLR-monitored mangrove stand. Poles were 10 cm in diameter, 2 m long, marked at every 10 cm with tape, and driven 1 m deep into the sediment.

4. mangrove bed-level dynamics
To monitor morphological responses of mangrove trees to the RSLR they experienced, each tree that received a water level logger, also received markings on ten pneumatophores to quantify responses in root-growth and bed-level dynamics. To this end, a cable-tie was tied to each pneumatophore at 10 cm from the tip, and at 10 cm from the bed. We randomly picked 3 other trees per site that received a similar treatment.

5. mangrove root acclimation
dataset 1: pneumatophore growth
See 4.mangrove bed-level dynamics.

dataset 2: rootmat formation:
To investigate how mangrove trees responded to experienced RSLR over the past decades, we rinsed out the root-zones of three living mangrove trees at three key sites (n = 3 per site). (1) Young trees, high RSLR rate and high sedimentation rates with respect to the tree (0 km from Semarang). (2) Old trees, high RSLR rate, and high sedimentation rates in the forest (3.3 km from Semarang). And (3), Young trees, low RSLR rate, and low sedimentation rate relative to the trees (20 km from Semarang).

dataset 3: sedimentation experiment:
The effects of extremely high sedimentation pulses were simulated in the field by exposing saplings (height = 60 cm, n = 6 per treatment group) and young trees (height = 2 m, n = 4 per treatment group) to a sediment increase of either 20 or 40 cm, with a control group where no sediment was added. A PVC tube (diameter = 30 cm) was put over the seedlings and filled with locally available sediment. The young trees were surrounded by fencing, constructed from bamboo and plastic and filled with sediment. Survival was assessed after 22 days at the end of that field visit, young tree survival was assessed after 60 days, at the start of the next field visit.

6. lateral mangrove die-back
dataset 1: Lateral mangrove erosion was quantified by counting the number of dead trees seaward of the mangrove fringe per 50 m coastline stretch at each of the 8 sites along the coast in the study area.
dataset 2: pneumatophore mortality
Loss of monitored pneumatophores gave a clear indication of lateral erosion as well, as marked pneumatophores (sample described in (4. Mangrove bed-level dynamics)) were often distributed around the tree, so 50% mortality of marked pneumatophores was often a result of lateral erosion in the field, which left the monitored tree at the seaward edge of the mangrove forest.
Pneumatophore survival per site was monitored two times in 1.5 years

Sampling strategy

No sample size calculations where performed. We have acquired the maximum amount of data possible within the limits set by our resources and challenging field conditions. The size of the data set is sufficient to detect significant correlations between measured parameters.

Data collection

0. Village population migration
collection procedure: not applicable, data are publicly available.
Who collected: central bureau of statistics of Demak Regency (Badan Pusat Statistik Kabupaten Demak)

1. village house experienced RSLR:
collection procedure: questionnaire led interviews
Who collected: distributed by a group of students and local volunteers who spoke the local language, coordinated remotely (due to covid) by Sri Ramadhani, co-author on this paper.

2. mangrove experienced RSLR
collection procedure: Small pressure sensors (Onset HOBO Water level logger U20L-04), which were covered with a sock (to prevent theft), were tied to the trunks of eight two mangrove trees in the eight monitored mangrove stands located along 20 km of study area. The loggers were configured to measure the pressure every 15 minutes, and were deployed for a period of 2.25 years. All sensors were located well above MSL, ranging from 22 until 27 cm above MSL. The sensors were cleaned and redeployed repeatedly. Whenever a sensor-tree was lost by a storm, a new sensor was deployed on a tree further inside the mangrove forest, anticipating future storms.
Who collected: The first author

2b. rainfall data
collection procedure: not applicable, data are publicly available.
Who collected: Badan Meteorologi, Klimatologi dan Geofisika (BMKG)

3. foreshore dynamics
collection procedure: Repeated visits (3 times) to monitoring poles that were placed at the start of the study. Scour around the pole was accounted for by using a level to bridge distance from the pole to the undisturbed bed. Water depth measured at the sedimentation pole was corrected to depth compared to MSL, at the time of water level measurement each campaign.
Who collected: First author

4. mangrove bed-level dynamics
collection procedure: Bed-level change inside the mangrove forest was monitored by measuring the distance from the bed to the cable tie that was fastened 10 cm from the bed at baseline. The four trees per site (8 sites) that were marked at the start of the study were revisited two times after baseline over the course of 1.5 years.
Who collected: First author

5. mangrove root acclimation

Date set 1: pneumatophore markings
collection procedure: Pneumatophore growth was monitored by measuring the length of each marked pneumatophore from the cable-tie (10 cm from the tip) to the tip upon each visit to the site. The four trees that were marked at the start of the study were revisited two times after baseline over the course of 1.5 years.
Who collected: First author

dataset 2: rootmat formation:
collection procedure: To investigate how mangrove trees responded to ongoing experienced RSLR over the past decades, we rinsed out the root-zones of three living mangrove trees with a 60 m^3 / h motorized water pump at three key sites. At each site, the number of distinctly separate rootmats per tree was quantified in the top 60 cm of the sediment, deeper excavation and rinsing was not possible.
Who collected: co-author: Corinne van Starrenburg

dataset 3: sedimentation experiment:
collection procedure: For experimental set-up, see field above. Survival of saplings and trees in the experiment was assessed after 22 days at the end of that field campaign, survival of trees was assessed again at the start of the next field visit (60 days later).
Who collected: co-author: Tom Heuts

6. lateral mangrove die-back
dataset 1: dead trees
collection procedure: Each site was approached by boat at low tide so that the trees with root zone were submerged. To get a general overview of the state of the mangrove fringe at the respective location, the number of dead trees within a 50 m stretch was counted alongshore, starting several meters from the boat. Thereby a 50 m measure tape was fixed (either on a tree or held), while one person walked along the coast counting the number of (visual) dead trees until the tape would reach its end. Fallen as well as standing trees were counted.
Who collected: co-author Corinne van Starrenburg
dataset 2: pneumatophore mortality
collection procedure: Pneumatophores that were marked for topic 5. “mangrove root acclimation” were monitored two times in 1.5 years, missing pneumatophores were noted as dead.
Who collected: first author

Timing and spatial scale

Spatial scale: The study area comprises the rural coastal area that stretches from the coastal plain East of Semarang harbour (-06° 56'47.40" S, 110°26'45.46" E), to the Wulan delta (-06°44'55.54" S, 110°33'57.70" E), (both outlined in black) 20 km to the Northeast. The entire area consists of alluvial deposits and sits above the same coastal aquifer that Semarang city draws its water from. The Wulan delta was chosen as a logical hydrological boundary to the study area.
For the mangrove and foreshore data we selected a site at every clearly defined mangrove stand between Semarang and the first big river mouth Northeast along the coast (at 12.5) km. We later decided to add one more reference site (20 km Northeast from Semarang, at the Wulan Delta), as the site at 12.5 km still seemed to be influenced by experienced RSLR at the time. This resulted in

the following mangrove sites at n km from Semarang (names for these mangrove sites are descriptive as the mangrove sites do not have official names):
0 Semarang
3,3 Bedono island
5,3 Bedono bay
7,1 Canal
8,5 Surodadi chenier
10 Surodadi planting
12,5 Tambakbulasan
20,1 Wedung

Similarly, to obtain information on village experiend RSLR, we included all coastal villages between Semarang and the first big river (at 12.5 km) and additionally also collected data at three more villages closer to the edge of the study area, to cover the full hypothesized subsidence gradient. Resulting in inclusion of the following villages at n km from Semarang (the village names are not specifically mentioned in the manuscript, but the spread of the measured houses across these villages is represented in Figure 2d):
SriWulan 0
SriWulan2 2,8
Bedono 5,1
Timbulsloko 6,5
Surodadi 8,8
Tambak Bulusan 11,8
Morodemok 13,8
Wedung 19
Berahan Kulon 21
Berahan Wetan 23,3

Temporal scale of the datasets:
0. Village population migration
We used migration data at village level from 2009-2010 to investigate how many people moved away from the area after a major shoreline change in 2009.

1. village house experienced RSLR:
Data were collected in August 2020.

2. mangrove experienced RSLR
Start date/ stop date: The loggers were deployed for a period of 2.25 years. The regular loss of trees and sensors ultimately led to five continuous pressure datasets that ran for more than 1 year (from April 2018 until October 2019).
Frequency: The loggers were configured to measure the water pressure every 15 minutes.
Periodicy: continuous, although the sensors were cleaned and redeployed twice after initial deployment.

3. foreshore dynamics
Start date/ stop date: August 2017 - October 2019
Frequency: revisited 3 times: April 2018, October 2018, October 2019.

4. mangrove bed-level dynamics
Start date/ stop date: April 2018 - October 2019
Frequency: revisited 2 times: October 2018, October 2019.

5. mangrove root acclimation
Start date/ stop date: April 2018- October 2019
Frequency: revisited 2 times: October 2018, October 2019.

dataset 2: rootmat formation:
Start date/ stop date: The rootmat dataset was collected during one field campaign (March-April 2018) and did not involve longer term monitoring.

dataset 3: sedimentation experiment:
Start date/ stop date: The sedimentation experiment was conducted during two field surveys (August 2017 and November 2017). The experiment was not monitored long term because the wet-season of 2017-2018 removed all trees from the site.

6. lateral mangrove die-back
dataset 1: The dead trees per 50 m coastline dataset was collected during one field campaign (March-April 2018) and did not involve longer term monitoring.

dataset 2: pneumatophore mortality
Start date/ stop date: April 2018 - October 2019
Frequency: revisited 2 times: October 2018, October 2019.

Data exclusions

0. Village population migration
no data was excluded

1. village house experienced RSLR:
Of the 194 houses in the original dataset, 5 houses were omitted from the experienced RSLR calculation, because they had raised their walls after raising the floor, or because they constructed an entirely new house where they already anticipated the flooding frequency and subsidence to come. The remaining 189 houses were plotted in the spatial map of village experienced RSLR.

To compare the village experienced RSLR with mangrove experienced RSLR, we only included villages the 10 of the 14 villages that were situated directly along the coast, and excluded the 70 houses that were located further inland. Resulting in a dataset of 119 houses across the 10 villages mentioned in the previous field of this form.

2. mangrove experienced RSLR
While originally all 8 mangrove sites of interest received two dataloggers, the regular loss of trees and sensors ultimately led to five continuous pressure datasets on trees across the studyarea that ran for more than 1 year, from which the tree-experienced RSLR rate could be quantified. Unfortunately, a linear regression through all water level logger points per logger over the full deployment time of each logger was not possible, because multiple loggers were deployed near a creek or river mouth. We observed a significant increase in water level over the wet season for those loggers, clearly caused by fresh-water run-off during the wet season. We could not correct for this effect because the discharge of each of the individual rivers and creeks was unknown. We therefore excluded the data from the wet-season, and only used tide-corrected water levels during the dry seasons. Significant differences in average tide-corrected water depths between two dry seasons were then tested with a two-sided independent t-test for each site. The resulting significant mean difference (+/- 95% CI) in average water depth between two consecutive dry seasons (a period of 60 days, exactly one year apart) was then used to calculate experienced RSLR rates. The site at 5.3 km from the subsidence epicentre site had an overlapping period of only 15 days, instead of 60 days between the two years, because the tree was lost shortly after re-deployment of the logger. Due to the critical location of this datapoint with respect to the assumed subsidence gradient, we decided to include the resulting mean experienced RSLR rate of this site for further analyses despite its wider confidence interval.

2b. rainfall data
No data was excluded from the timeframes of interest (dry season 2018 and dry season 2019)

3. foreshore dynamics
Each site originally received two monitoring poles at 50 m from the mangrove fringe. Unfortunately, we only recovered one pole at most sites that could be revisited. We excluded the site 10 km from Semarang from the analysis, as that sedimentation pole was repeatedly removed by people. 7 of the 8 sites thus had one foreshore pole, which was visited 4 times, resulting in principle in 4 depth replicates, and 3 bed-level change replicates. However, at the two most eroding sites (0 and 3.3 km from Semarang), the erosion rates were so high that the PVC poles were lost within the first 8 months of deployment. The depth of the original pole location had become too deep (subtidal) for deployment and monitoring of a new PVC pipe. Especially the monitoring of a subtidal pole was found to be unfeasible, as locating a submerged PVC pipe with GPS during follow-up visits was impossible due to the turbid water, and marker buoys were lost. The new location therefore had to be more shallow than the original location, and the most meaningful choice was therefore to place the new pole 50 m out of the retreated mangrove fringe. The placement of the two new poles at a more shallow location, meant that for these two sites there was no continuous bed-level dataset, which would have contained increasingly deeper bed-levels. The foreshore depth data at presented for these sites therefore represent a conservative average foreshore depth at subsiding sites. The loss of the original monitoring poles at these two sites, also meant the absence of bed-level change measurements for those sites. We therefore assumed a conservative 60 cm of vertical erosion compared to baseline between the first two monitoring campaigns. This amount of erosion would have toppled over the pole with its original 1 m anchoring depth. Sixty cm appeared to be a conservative estimate of the amount of erosion that had occurred, based on the observed depth at the original locations of these two poles 8 months after initial deployment. The sites at 12.5 km and 20.1 km from Semarang were added later to the monitoring gradient and therefor only have 3 replicates in time for depth and 2 replicates for bed-level change.

4. mangrove bed-level dynamics
Due to lateral loss of monitoring trees and damage to remaining marked pneumatophores in the second year of monitoring, only the mangrove response data of the first 8 months were used to compare the vertical bed-level changes inside the mangrove forest between sites along the coast, resulting in growth data of 162 pneumatophores belonging to 22 trees across the study area.

5. mangrove root acclimation
Dataset 1: pneumatophore markings
While we visited all sites at 7 months and 19 months after baseline, we decided only to use the mangrove response data between t0 and t7, as lateral tree loss and pneumatophore damage over the consecutive monitoring year (between t7 and t19) made the cable-tie to tip measurements less representative of pneumatophore growth. The effect of experienced RSLR on pneumatophore growth was tested at the sites where bed-level change inside the fringe was negative or zero over the period of the study (sites > 5 km from Semarang). To investigate the effect of experienced RSLR on pneumatophore growth under limited accretion, we performed a linear mixed effects model, using experienced RSLR as explanatory variable (fixed factor) and tree as a random effect, because pneumatophores were nested per tree. Sites that we did not have experienced RSLR data for were excluded from the analysis, resulting in 85 observations of pneumatophore growth nested within 12 trees.

Dataset 2: rootmat formation:
no data were excluded

dataset 3: sedimentation experiment:
no data were excluded

6. lateral mangrove die-back
dataset 1: dead trees
no data were excluded
dataset 2: pneumatophore mortality
no data were excluded, however, data for two sites (at 8.5 and 10 km from Semarang) were not collected.

Reproducibility

All field derived data have not been attempted to reproduce, this was not possible due to the temporal aspect of the data collection. The sedimentation experiment has been conducted as a pilot with only 0 and 20 cm of sedimentation prior to the fieldcampaign of August 2017. Seedlings in those treatmens prooved equally resilient to sedimentation as the seedlings and young trees reported in this paper.

Randomization

Data collection procedure
0. Village population migration
Not applicable

1. village house experienced RSLR:
No randomization was applied for house selection. We needed to find older houses that had already been subject to RSLR to be able to calculate experienced RSLR rates based on house parameters. Houses were thus selected based on age and willingness of residents to participate in the study.
2. mangrove experienced RSLR
No randomization was applied to select mangrove sites for this study. The eight mangrove stands that were monitored were selected because they were clearly defined mangrove stands between Semarang and the first big river mouth Northeast along the coast (at 12.5) km. We later decided to add one more reference site (20 km Northeast from Semarang, at the Wulan Delta), as the site at 12.5 km still seemed to be influenced by experienced RSLR at the time.
At sites, trees on the mangrove edge were initially selected to attach the loggers to, to make sure that the pressure loggers would be as much in the water as possible to collect the valuable water level data. However, the first wet season revealed how vulnerable those trees were, as we lost many of our trees and loggers. Therefore during the next campaign in April 2018 we redeployed loggers on trees that seemed sturdy and were located at least 50 m from the fringe, anticipating erosion over the next wet season.

3. foreshore dynamics
No randomization was applied, monitoring poles were placed 50 m offshore from the trees that were being monitored within the mangrove stands of interest.
4. mangrove bed-level dynamics
No predetermined randomization was applied, three additional trees nearby the "logger tree" were selected as replicates, to ensure that environmental conditions were similar. Neighbour trees were selected to ensure that trees could be retraced and were accessible within the limited timeframe in which the sites could be visited, due to the difficult field conditions.

5. mangrove root acclimation
Date set 1: pneumatophore markings
See: 4. Mangrove bed-level dynamics
dataset 2: rootmat formation:
The three trees per site were selected, based on stem size, which had to be similar between the 0 km and 20 km sites to ensure a similar tree age between those sites. The accessibility also played a role, as the trees could not be further than 15 m landwards from the shore because of the pump hose length.
dataset 3: sedimentation experiment:
The sedimentation experiment was done at a location where multiple young trees and seedlings were available in close proximity, but not yet intertwined in their root systems. All young trees at the site that had the potential to be treated with a sedimentation treatment (i.e. were isolated enough from their neighbours), were measured in length and diameter (of the thickest stem).
These parameters were then used to divide the trees among the three treatment groups to ensure similarity between groups, the same was done for the seedlings.

6. lateral mangrove die-back
dataset 1: dead trees
no randomization was applied, the same sites were used as mentioned for the bed-level and pneumatophore growth datasets.
dataset 2: pneumatophore mortality
See: 4. Mangrove bed-level dynamics

Blinding

not applicable

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions

Field work along the foreshore was carried out as much as possible during the calm seasons (dry season: June-August, pre-wet season: Sep-Nov, and post-wet season: Mar-May. Foreshore and mangrove sites were accessed by wooden boats. Mangrove sites were usually visited around high tide, when the mudflats were submerged and the sites were easily accessible by boat. The furthest sites were an hour boatride from the field accomodation, which significantly reduced the time window that we could spend in the mangrove forest before the tide started falling again and and we had to go back. For some dataset sets (e.g. the dead tree dataset), low tide conditions were required. This made fieldwork extra challenging as the fluid mud of the mudflats did not allow for easy walking. In many places we would sink in to our knees, and in some cases even to our hips. During the transitional seasons in November and March, we also experienced the occasional tropical storm and rough seas which made it harder to access some of the sites. Especially since the boats that we used were small wooden perahu's, used by the nearshore fishermen, these boats were not built to withstand the larger onshore swell waves during the wet season, which is the main reason that we could not visit the mangrove sites during that season.

Location

see Timing and Spatial Scale field.

Access & import/export

This research was carried out with the appropriate research permits, issued by Ristek Dikti in 2018 and 2019, under the permit numbers: 330/SIP/FRP/E5/Dit.KI/X/2018 and 72/E5/E5.4/SIP.EXT/2019.

Disturbance	Any foreign materials that were brought to the field, such as plastic cable ties for the tree markings, and plastic surrounds around trees were removed as much as possible upon ending of experiments. Unfortunately, the covid pandemic did prevent the authors from going back one more time to do a final monitoring round and removal of cable-ties on pneumatohpores. This unfortunately means that these cable ties will add to the plastic pollution that this area is already subjected to.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging