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Restoration of declining soil carbon stocks and lost surface elevations in degraded mangroves on the northern coast of Java, Indonesia

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Restoring degraded coastal zones could help to stem the loss of carbon (estimated by soil carbon differences) and soil surface elevations (measured through rod surface elevation table and marker horizon) due to mangrove conversion and sea-level rise. In mangroves, total ecosystem carbon stocks are primarily stored in soil, however the presence of vegetation remains crucial. When we assessed soil carbon across contrasting land uses in Wedung and Sayung Districts in Demak Regency, Central Java, we found that converting mangrove to aquaculture increased soil carbon by 17.68 Mg C ha^{-1} in Wedung but decreased it as much as 62.58 Mg C ha^{-1} in Sayung. Meanwhile, abandonment of ponds resulted in a loss of 34.24 Mg C ha^{-1} in Wedung but a gain of 8.81 Mg C ha^{-1} in Sayung. The estimated local sea-level rise of 0.45 cm yr^{-1} led to relative sea-level rises of 5.56, 6.82, and 1.36 cm yr^{-1} in mangroves, working and abandoned ponds respectively in Wedung, and 8.00, 10.39, and 10.46 cm yr^{-1} respectively in the same environments in Sayung. This indicates that Sayung is more severely inundated. After considering land subsidence levels, only mangroves in Wedung experienced an elevation surplus of 2.02 cm yr^{-1}. The remaining land uses suffered elevation deficits, hence being inundated by 1.86 and 15.00 cm yr^{-1} in abandoned ponds in Wedung and Sayung respectively. Despite variation in this study's findings, some scenarios could be considered useful to support relevant coastal areas to enhance soil carbon stocks or surface elevation.

KEYWORDS

abandon, aquaculture, conversion, Demak, susceptibility, sea-level rise, subsidence, accretion

1 Introduction

Mangroves are salt-tolerant vegetation that grow in intertidal zones (Hogarth, 2015). They provide spawning grounds for fish (Arceo-Carranza et al., 2021), shoreline protection from storm events (De Dominicis et al., 2023), and an effective pool for carbon (Donato et al., 2011). Beyond their ecological benefits, mangroves support the livelihoods and well-being of people living on the coast via tourism (Spalding and Parrett, 2019), traditional medicine (Bandaranayake, 1998), and food sources (Damastuti and De Groot, 2019). Despite their significance, mangroves are seriously threatened by land-use change practices.

Sixty-two percent of global mangrove area was lost between 2000 and 2016 due to their transformation for agricultural and aquaculture purposes (Goldberg et al., 2020). In Indonesia – the country with the largest expanses of mangrove – rampant aquaculture development has reduced mangrove cover from 1980 to 2005 by 52,000 ha yr^{-1}, emitting about 0.175 Pg CO_2 yr^{-1} (Murdiyarso et al., 2015). Specifically, in Mahakam Delta of Indonesia, Arifanti et al. (2019) demonstrated that each kilogram of black tiger shrimp produced in mangrove-converted ponds led to 2,250 kg CO_2e released, equivalent to burning 2,074 litres of gasoline. As mangrove soil makes up to 85% of the total mangrove ecosystem carbon stocks (Malik et al., 2023), soil disturbances through mangrove conversion activities are responsible for 81% of total carbon emissions (Kauffman et al., 2018). This is because once mangroves are converted to aquaculture ponds, soils are exposed to oxygen, which leads to increased microbial activities and carbon emissions. This problem becomes even more complex, as converted ponds are abandoned. In Indonesia, around 250,000 hectares of ponds have been abandoned after use (Gusmawati et al., 2018). Pond abandonment is often linked to and exacerbated by many forms of environmental degradation, including disease outbreaks, compacted soil, sea-level rise (SLR), low productivity, and dyke collapse (Bosma et al., 2012; Arifanti et al., 2019; Aslan et al., 2021). A case study in Indonesia found that abandoned ponds resulted in higher greenhouse gas emissions (30.6 ± 1.9 Mg CO_2e $ha^{-1}yr^{-1}$) than active ponds in use (1.1 ± 0.2 Mg CO_2e ha^{-1} yr^{-1}) (Cameron et al., 2019).

Converting mangroves to ponds not only releases a vast amount of soil carbon to the atmosphere but also reduces the soil surface elevation. Mangrove roots can help trap autochthonous (native to the location) and allochthonous (from a different location than where found) soils and, therefore, promote additional soil surface elevation (Krauss et al., 2003; Norris et al., 2019; Sasmito et al., 2020a). As mangroves are removed, these areas probably experience surface elevation change (SEC) due to processes beneath the ground (Ravelonjatovo et al., 2024). Surface elevation change depends on both surface accretion rate (SAR) and sub-surface change (SSC). Surface accretion rate refers to the upper soil layer, in which we see vertical accretion or erosion depending on root complexity and hydrogeomorphic settings; while SSC refers to shallow underground soil processes (decomposition, compaction, root growth/mortality, soil shrink/swell), which result in land uplift or subsidence (Krauss et al., 2014). A reduction in SEC rate might make coastal lands more susceptible to SLR as it results from ocean thermal expansion and ice melting, as a consequence of global warming (Warrick and Oerlemans, 1990; Church and White, 2011). At local scale, the rate of SLR varies as coastal lands can uplift or subside. Hence, measuring the change in mean sea level to surface land in any given area (also known as relative sea-level rise, RSLR) can be used to evaluate the response of coastal lands to rising sea levels (Church et al., 2013). Higher RSLR causes coastal land position to be lower than the sea level, making these areas more vulnerable to submergence in the future (Cahoon, 2014; Lovelock et al., 2015).

The impacts of mangrove conversion and pond abandonment on carbon release can be estimated by the difference in soil carbon stocks between two land-use types by assuming equivalent soil mass (Ellert et al., 2008). Meanwhile, the susceptibility of coastal land to rising sea levels is commonly evaluated by comparing the rate of SEC and RSLR (subsidence + SLR) (McIvor et al., 2013). Surface elevation change and subsidence on the coast are widely investigated by measuring rod surface elevation tables and marker horizons (rSETs-MHs) in the field (Cahoon, 2014), while SLR is commonly quantified by analyzing the sea-level anomaly trend from satellite data around the study location (Firdaus et al., 2023). One of the advantages of utilizing satellite altimeters over tide gauges is their independence from vertical land motion (Fenoglio-Marc et al., 2012).

Located in the northern coast of heavily populated Central Java, Demak Regency is characterized by contrasting coastal morpho-dynamics, especially in the north (Wedung) and south areas (Sayung) (Winterwerp et al., 2014). Wedung has experienced accretion due to suspended material sedimentation from the Wulan River, creating the Wulan Delta and mangrove habitats (Ervita and Marfai, 2017). However, part of this delta was converted to aquaculture between 2000 and 2010 (Marfai et al., 2016). Due to their low productivity and higher operational costs, owners usually abandon their ponds (pers. comm. local communities). Meanwhile, in Sayung, mangrove deforestation for aquaculture purposes, tidal flooding, and wave actions have resulted in massive shoreline retreat (Marfai, 2011; Muskananfola et al., 2020). Tidal flooding frequently occurs in Sayung, as this region has experienced more significant land subsidence (reaching up to 8 cm yr^{-1}) compared to the northern part of Demak (Sarah et al., 2020; Aditiya and Ito, 2023). Moreover, tidal flooding and wave energy have destroyed pond dykes and triggered the abandonment of ponds in Sayung.

Such situations make Demak Regency an ideal area to investigate the loss of soil carbon and surface elevation due to land-use change, as mangrove conversion and pond abandonment have been found in many places along the coast (Marfai et al., 2016; Damastuti and De Groot, 2019). Mangroves play a crucial role in storing significant amounts of carbon and promoting soil elevation gain through sediment accumulation and organic matter buildup (Donato et al., 2011; Krauss et al., 2014). Based on these characteristics, we hypothesize that mangrove areas retain more soil carbon and experience less elevation loss compared to working and abandoned ponds. To test this hypothesis, this study aimed to (1) estimate carbon stock changes from soil due to mangrove

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conversion and pond abandonment activities, and (2) assess the elevation change in coastal areas related to those practices (looking at mangroves, working ponds, and abandoned ponds). We focused on and considered Wedung and Sayung Districts as these areas have contrasting coastal morpho-dynamics.

Information around the implications of mangrove transformation and pond abandonment is expected to provide valuable input for stakeholders and decision-makers, especially in Demak. This study could provide a useful reference in determining better coastal land management strategies to prevent the loss of soil carbon and surface elevations that contributes to mitigating climate change conditions.

2 Study site and methods

2.1 Site description

This study was conducted in Demak Regency, Central Java, Indonesia. The region has a rainfall of 2,248 mm yr^{-1}, with lower rates occurring from May to October, and higher rates between November and April (Supplementary Figure S1; BMKG, 2022). Coastal Demak has a tidal range between 0.4 and 0.6 m (micro-type) (Smits, 2016; Tas et al., 2020) and a surface slope of less than 2%, 0–5 m height above sea level, is low-lying land (Subardjo, 2004; Marfai et al., 2016).

Research in Demak was carried out specifically in Wedung (6° 45' 29.45" S and 110° 33' 49.43" E) and Sayung (6° 53' 48.58" S and 110° 30' 24.59" E) Districts. In each district, research plots included three mangroves, three working ponds, and three abandoned ponds. To assess carbon and elevation dynamics across land uses, this study evaluates total ecosystem carbon stock (TECS) and SEC. For TECS assessment, mangroves were evaluated using six circular sub-plots for the biomass and soil pools (Supplementary Figure S2; Kauffman and Donato, 2012), while the planar intercept technique was applied for wood debris (Supplementary Figure S2; van Wagner, 1968). In contrast, only soil sampling was conducted in working and abandoned ponds. Furthermore, SEC was measured across all plots (Figure 1). At the mesoscale (focusing on hydrogeomorphic features), the study area was classified as an interior system. Meanwhile, at the macroscale setting (considering larger hydrodynamic and tidal influences), it was categorized as an estuary (Lugo and Snedaker, 1974; McKee, 1993; Woodroffe et al., 2016; Worthington and Spalding, 2018).

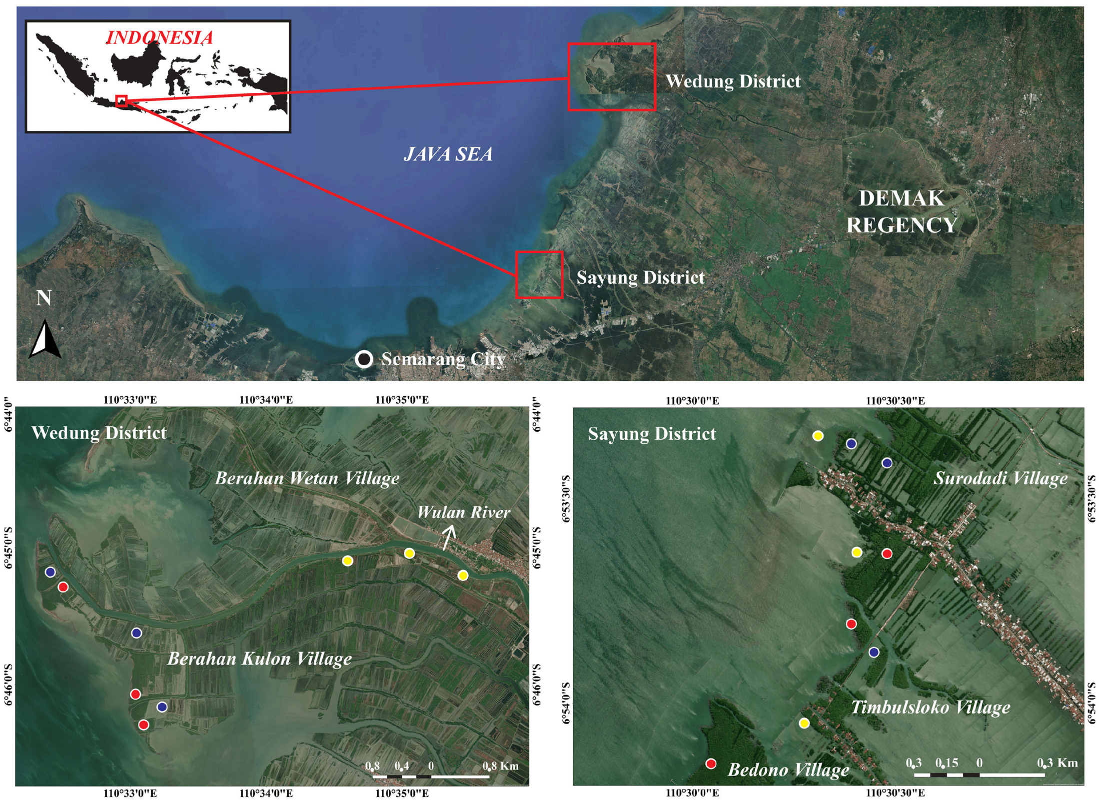

FIGURE 1
Map showing the location of sampling sites in Wedung and Sayung. Red dot (●) indicates mangroves, blue dot (●) indicates working ponds, and yellow dot (●) indicates abandoned ponds. The map was created using Esri's ArcGIS 10.7 desktop GIS software.

2.2 Quantification of total ecosystem carbon stocks

Total ecosystem carbon stock in mangroves was quantified from aboveground and belowground biomass, wood debris, and soil pools. Biomass carbon stock was estimated by measuring the diameter at breast height (DBH), following the recommendations by Pearson et al. (2005). Diameter at breast height measurements were conducted for saplings (DBH< 5 cm) and trees (DBH > 5 cm), with saplings measured within a 2-meter radius and trees within a 7-meter radius of the circular subplot (Kauffman and Donato, 2012). In addition to DBH, mangrove species and stand status (live or dead) were recorded, with species identification based on the vegetation identification book specific to Indonesian mangroves (Kitamura et al., 1997). Standing dead trees were classified into three decay statuses based on Kauffman and Donato (2012): Status 1, where small branches and twigs had been lost but leaves were still present; Status 2, where small and large branches had detached, leaving no twigs; and Status 3, where the main stem had few or no remaining branches.

Carbon stock in woody debris, consisting of fallen branches and twigs, was measured along the diagonal transects of the previously established circular subplots. Each subplot contained four 12-meter-long transects, divided into four sections: 0–2 m, 2–7 m, 7–10 m, and 10–12 m. Large, decayed, rotten and sound wood (diameter > 7.6 cm) was measured along the full 12-meter transect, medium-sized wood (diameter 2.5 > 7.6 cm) within the 2–7 m section, small wood (diameter 0.6 > 2.5 cm) within 7–10 m, and fine wood (diameter 0 > 0.6 cm) within 10–12 m (Kauffman and Donato, 2012). Only fallen branches or twigs crossing the transect were recorded, and their diameters were documented based on wood debris classification.

For soil carbon assessment, soil samples were collected from each circular subplot at depths of 0–15 cm, 15–30 cm, 30–50 cm, 50–100 cm, and 100–300 cm (Kauffman and Donato, 2012). We used open-face and closed-face augers, along with extensions, all made of stainless steel. The open-face auger was primarily used; however, in water-rich soils, such as those found in certain working ponds, the closed-face auger was preferred due to its secure mechanism, which prevents soil from slipping out easily during extraction. For non-mangrove areas, only soil sampling was conducted, as biomass and wood debris were either minimal or entirely absent in the study sites. Additionally, standardized methods for measuring biomass and wood debris in working and abandoned ponds are not yet well established. Since each core contained five soil samples, we collected a total of 180 samples from mangroves, 90 samples from working ponds, and 90 samples from abandoned ponds. All samples were processed separately.

To quantify carbon stocks, allometric equations were used to estimate above- and below-ground biomass (Supplementary Table S1). The allometric equation used in this study requires data on DBH, wood density, and the decay status of each recorded stand. While DBH and decay status were obtained from field measurement, wood density value was sourced from ICRAF (2022). However, aboveground biomass in standing dead trees was estimated by subtracting its value to 2.5%, 20%, and 50% of biomass for tree decay level 1, 2, and 3, respectively (Kauffman and Donato, 2012). Standard multiplier carbon concentrations of 0.47 and 0.39 were employed to convert aboveground biomass to aboveground biomass carbon stock, and belowground biomass to belowground biomass carbon stock (Kauffman and Donato, 2012).

Following Kauffman and Donato (2012), woody debris carbon stock was estimated considering the volume of each type of debris, and the specific gravity as reported by Castillo et al. (2018). In addition, an acceptable default value for carbon content (50%) was used to estimate woody debris carbon stocks (Kauffman and Donato, 2012). Furthermore, soil bulk density, carbon content, and carbon–nitrogen (C-N) ratio were estimated through laboratory activities and calculated following Kauffman and Donato's (2012) methodology. The process began by drying the soil samples at 40°C until they reached a constant mass. Each dried sample was then weighed to 40 milligrams for carbon content analysis using the dry combustion technique in an elemental analyzer. Soil bulk density was calculated by dividing dry soil mass by sample volume (Kauffman and Donato, 2012). Finally, TECS was obtained by summing up carbon stocks from aboveground biomass, belowground biomass, woody debris, and soil.

2.3 Calculation of soil carbon differences

Coastal land use change, such as converting mangroves into aquaculture ponds, typically affects soil properties within the first meter of depth. Therefore, this study quantified soil carbon stock differences down to 1 m soil depth using an equivalent soil mass approach (SOC_{FM}, in Mg C ha^{-1}), as developed by Ellert et al. (2008) and suggested by Andreetta et al. (2016), as shown below:

$$SOC_{FM} = (\Sigma\, OC \times BD \times D_h \times 0.1) - \frac{M_{ex} \times OC_{ds}}{1000}$$

where OC is organic carbon content for each soil depth layer (mg g^{-1}), BD is bulk density (g cm^{-3}), D_h is soil thickness interval (cm), M_{ex} is the excess mass of soil (g), and OC_{ds} is organic carbon content in the deepest soil interval (mg g^{-1}).

2.4 Assessment of surface elevation change, surface accumulation rate, and sub-surface change

A protocol for monitoring wetlands elevation dynamics put forward by Lynch et al. (2015) was primarily followed during the installation and measurement of rSET-MH. Moreover, mesh plate was selected as MH in this work (Swales and Lovelock, 2020). In total, 18 rSETs and 36 MHs were established across 18 study plots in Demak; these were observed from 25 January to 23 November 2022.

Using a millimeter resolution ruler and bimonthly monitoring of rSETs and MHs, the same observer recorded SEC and SAR. Following Cahoon et al.'s (1995) formula, the SSC was estimated as:

$$SSC = SAR - SEC$$

Positive SSC indicates subsidence and negative SSC_s shows land uplift. In this study, the subsidence we refer to occurs in the sub-surface soil layer, where biophysical surface processes take place. Cahoon et al. (1995) also referred to process as 'shallow subsidence', which is not the same as the deep subsidence that is influenced by geological activity.

2.5 Estimation and evaluation of sea-level rise, relative sea-level rise and wetland relative sea-level rise

Sea-level rise was estimated by applying the 'trend' function in the Climate Data Toolbox (Greene et al., 2019). Analysis was done by averaging grid point data within each studied district. This study used satellite altimetry data – provided via data.marine.copernicus.eu – to examine monthly global ocean sea-level anomaly. To do so, grids of 0.25° x 0.25° were examined, focusing on data between 1993 to 2021 in the Java Sea close to Demak coast. The trend of sea-level anomaly – established from the satellite altimetry data – was compared to sea-level data from the nearby tide gauge (6° 56' 52.44" S and 110° 25' 12.43" E) to obtain correlation coefficients and a root mean square difference (Emery and Thomson, 2001). Due to limited accessible data, missing data, and errors in the tide gauge reference data, only the period from January 2013 to January 2017 was compared between these two datasets. Meanwhile, RSLR was quantified by adding the SLR rate to the subsidence rate (Cahoon et al., 1995).

The wetland RSLR ($RSLR_{wet}$) rate was quantified using the following formula, derived by Cahoon (2014), to evaluate the dynamic of surface elevation in mangrove and non-mangrove areas in response to sea level:

$$RSLR_{wet} = RSLR - SEC$$

A positive $RSLR_{wet}$ reveals an elevation deficit due to sea levels rising above the wetland surface. Meanwhile, a negative value represents an elevation surplus, caused by a sea level that is declining relative to the wetland surface (McIvor et al., 2013; Cahoon, 2014).

2.6 Statistical analyses

Rstudio version 2023.12.0 was used to statistically analyze the data, supported by package 'agricolae' (De Mendiburu, 2009). The normality of the data distribution was examined by Shapiro-Wilk test. Two groups of samples (SSC and RSLR between Wedung and Sayung Districts) were compared through an unpaired T-test (for normally distributed data) and Wilcoxon rank sum test (for non-normally distributed data). A two-way analysis of variance test (for normally distributed data) and a Kruskal-Wallis rank sum test (for non-normally distributed data) were then carried out to compare more than two groups of samples; this included comparisons of carbon storage among pools and land-use types, as well as comparing SEC, SAR, SSC, RSLR, and wetland RSLR across land-use types. *Post-hoc* analysis (Tukey Honestly Significant Difference test) was performed when tests for more than two sample groups showed significant differences, such as carbon stocks across pools, as well as soil C stocks, SEC, and SAR among coastal land-use types.

3 Results

3.1 Total ecosystem carbon stocks

Total ecosystem carbon stocks in mangroves in Wedung and Sayung were 707.90 ± 27.69 Mg C ha^{-1} and 750.35 ± 56.54 Mg C ha^{-1}, respectively (p > 0.05) (Figure 2). Among carbon pools, soil had the highest carbon stocks (p< 0.05), estimated at 618.84 ± 30.39 Mg C ha^{-1} (87%) in Wedung and 688.07 ± 52.97 Mg C ha^{-1} (92%) in Sayung. In Wedung, there was a significant variation of soil carbon among land-use types (p< 0.05), with the lowest soil carbon stocks found in mangroves, and the highest in working ponds (1234.51 ± 165.00 Mg C ha^{-1}). In contrast, most of soil carbon in Sayung was stored in mangroves (688.07 ± 52.97 Mg C ha^{-1}), while the least was stored in working ponds (365.60 ± 186.34 Mg C ha^{-1}). Nevertheless, the variation was non-significant (p > 0.05) (Figure 2). Supplementary Table S2 presents the soil carbon stock at different depth layers for mangroves, working ponds, and abandoned ponds.

The differences in soil carbon stock from mangroves to working ponds, and from working ponds to abandoned ponds, varied between the two sites. In Wedung, 17.68 Mg C ha^{-1} less soil carbon stock was found in mangroves than working ponds (Supplementary Figure S3a). Otherwise, soil carbon stocks in working ponds were higher 34.24 Mg C ha^{-1} than in abandoned ponds. Moreover, mangroves in Sayung had greater soil carbon storage at 62.58 Mg C ha^{-1} compared to working ponds. However, soil carbon stocks in working ponds were greater 8.81 Mg C ha^{-1} than in abandoned ponds. Differences in soil carbon stocks can occur due to soil property dynamics like bulk density (Supplementary Figure S3b), carbon content (Supplementary Figure S3c), and C-N ratio (Supplementary Figure S3d).

3.2 Surface elevation change, surface accretion rate, and sub-surface change

All land uses in Demak Regency mostly experienced lower SEC than SAR from January to November (Figure 3). Therefore, subsidence occurred during the observation except for abandoned ponds in Wedung District. Average rates of subsidence can be seen in Table 1.

Overall, a positive SEC was found in mangroves (Wedung: 7.58 ± 0.77 cm yr^{-1} and Sayung: 1.46 ± 4.41 cm yr^{-1}) and working ponds (Wedung: 0.38 ± 0.82 cm yr^{-1} and Sayung: 2.83 ± 1.53 cm yr^{-1}) (Table 1). However, SEC was negative in abandoned ponds (Wedung: -0.50 ± 0.91 cm yr^{-1} and Sayung: -4.54 ± 2.52 cm yr^{-1}) owing to the SAR being lower than the subsidence rate. Statistically,

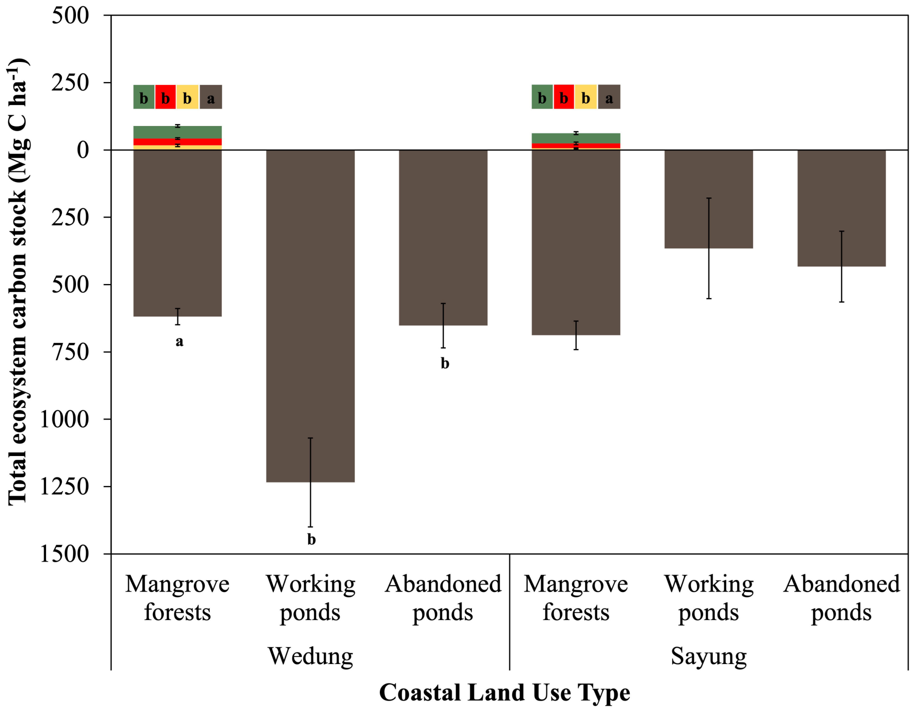

FIGURE 2
Carbon stored in aboveground biomass (), belowground biomass (), woody debris biomass (), and soil () (Mg C ha^{-1}) (mean ± standard error in Mg C ha^{-1}). Letters above and below the bar indicate their significant difference when they are different (p< 0.05).

a considerable variation was only found in SEC and SAR in mangroves, working ponds, and abandoned ponds located in Wedung (Table 1; p< 0.05). In contrast, there were no significant differences in subsidence rate across land-use types in both Wedung and Sayung. A considerable difference in subsidence was found between Wedung and Sayung (p< 0.05).

3.3 Sea-level rise and relative sea-level rise

Based on the evaluation of sea-level anomaly trends over 29 years, SLR in Demak was estimated at 0.45 cm yr^{-1} (Figure 4). The satellite data and tide gauge data analyzed in this study were in agreement, with a coefficient correlation and root mean square difference of 0.82 and 3.18 cm. SLR led to RSLR variation in different months and land-use types (Supplementary Figure S4). The RSLR in each district showed no considerable variation across land-use types (Table 2; p > 0.05). However, RSLR differed statistically in abandoned ponds between Wedung and Sayung (p< 0.05). The RSLR values among land use types were lower in Wedung than Sayung.

3.4 Wetland relative sea-level rise

The wetland RSLR dynamics observed in mangrove and non-mangrove (i.e., working and abandoned ponds) areas can be seen in Supplementary Figure S4. This study did not find significant variation of wetland RSLR value across land-use type in each region (p > 0.05). However, elevation surplus in Wedung (–2.02 ± 1.65 cm yr^{-1}) was only found in mangroves (Table 2). Similarly, mangroves had the lowest elevation deficit (6.54 ± 6.06 cm yr^{-1}) in Sayung. Non-mangrove areas experienced more severe elevation deficits, both in Wedung and Sayung. In Wedung, the elevation deficit was 6.44 ± 5.48 cm yr^{-1} in working ponds and 1.86 ± 1.69 cm yr^{-1} in abandoned ponds. Working and abandoned ponds in Sayung had elevation deficit values of 7.56 ± 4.20 cm yr^{-1} and 15.00 ± 3.22 cm yr^{-1}, respectively.

4 Discussion

4.1 Soil carbon difference from mangrove conversion and pond abandonment practices

This study provides empirical evidence about carbon stock changes in the context of mangrove conversion. While mangrove conversion has been widespread in Southeast Asia (Goldberg et al., 2020) the resulting carbon stock changes have not been reported for critical areas such as Demak. Mangroves at our two sites in Demak – Wedung and Sayung (Figure 2) – had lower TECS than the average for mangroves in Indonesia (1,083 ± 378 Mg C ha^{-1}) (Murdiyarso et al., 2015), but higher TECS than found in degraded mangroves in Cambodia (621.7 ± 89.3 Mg C ha^{-1}) (Sharma et al., 2020). Carbon stocks were primarily found in soil in Wedung (87%) and Sayung (92%); these percentage are within

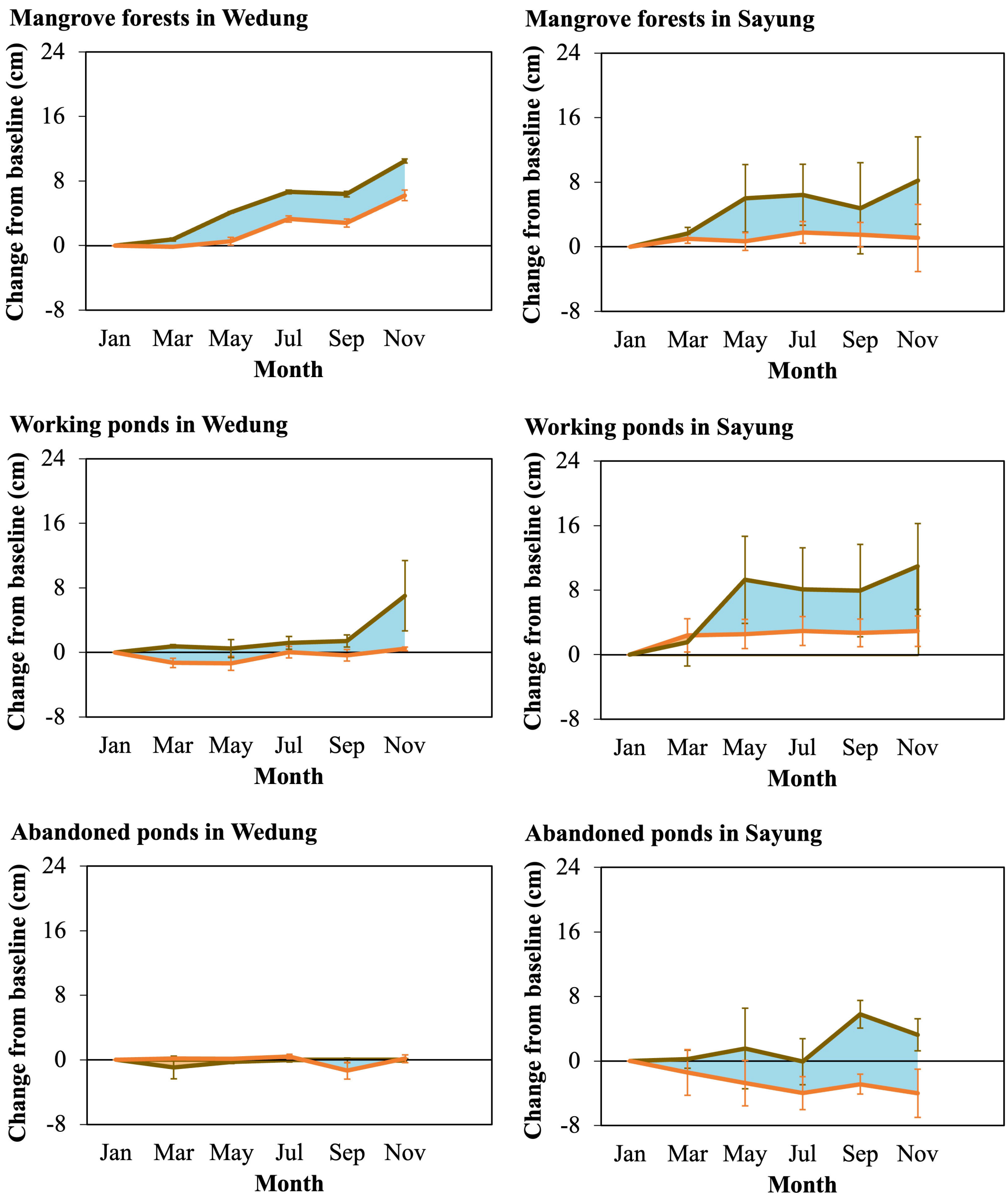

FIGURE 3
Cumulative surface elevation change (orange line), surface accretion rate (brown line), subsidence (blue box), and land uplift (orange box) in mangroves, working ponds, and abandoned ponds in Wedung and Sayung Districts (mean ± standard error in cm).

the range of soil carbon contributions to TECS reported by Sasmito et al. (2020b), who found contribution percentages to range between 71–94% in Papuan mangroves in Indonesia.

The practices of mangrove conversion and pond abandonment in Wedung and Sayung caused surprising results in terms of soil carbon stock differences. First, converting mangroves into working ponds in Wedung led to an increase in soil carbon stock (Supplementary Figure S3a). This was likely caused by the suspended sediment supply (which may contain carbon) from the wide Wulan River (Ervita and Marfai, 2017) entering the ponds and/or waste production from aquaculture. In contrast, the same practice in Sayung led to a decrease in soil carbon stock (Supplementary Figure S3a). This value was greater than another study in Sawah Luhur Village in Banten Province, Indonesia, which decreased from 108.60 to 69.45 Mg C ha^{-1} when mangroves were converted to aquaculture (Royna et al., 2024). This was likely caused by a decrease in the amount of organic matter in ponds due to increased decomposition rate, especially after ponds were drained (Arifanti et al., 2019; Eid et al., 2019). The post-conversion soil carbon losses reported in this study could be underestimated, as the carbon stored in mangrove biomass has not been considered in our soil carbon stock difference assessment.

TABLE 1 Variations in surface elevation changes, surface accretion rates, and subsidence rates in mangroves, working ponds, and abandoned ponds (mean ± standard error in cm yr^{-1}).

Region/Land-use types	Surface elevation change (cm yr^{-1})	Surface accretion rate (cm yr^{-1})	Sub-surface change (cm yr^{-1})
Wedung			
Mangroves	7.58 ± 0.77[a]	12.69 ± 0.26[a]	5.11 ± 0.89
Working ponds	0.38 ± 0.82[b]	6.75 ± 3.89[ab]	6.37 ± 4.68
Abandoned ponds	(–) 0.50 ± 0.91[b]	0.41 ± 0.88[b]	0.91 ± 1.00
Sayung			
Mangroves	1.46 ± 4.41	9.00 ± 7.40	7.55 ± 5.13
Working ponds	2.83 ± 1.53	12.77 ± 6.12	9.94 ± 5.02
Abandoned ponds	(–) 4.54 ± 2.52	5.47 ± 2.28	10.01 ± 1.19

Letters next to the numbers indicate their significant difference when they are different ($p < 0.05$). Positive values in sub-surface changes indicate shallow subsidence.

Ponds are abandoned after several years of operation, leaving unproductive landscapes in coastal areas. Higher soil carbon stocks in working ponds than in abandoned ponds in Wedung implies a release of carbon (Supplementary Figure S3a) from a 1-meter soil depth. These soil carbon losses might be caused by draining and restricting tidal currents, likely promoting aerobic conditions that favor carbon oxidation (Arifanti et al., 2019). Currently, there is still insufficient data to acknowledge the soil carbon stock differences between working and abandoned ponds. However, this study is in line with research results in Sulawesi, Indonesia, which found that emissions were lower in working ponds (1.1 ± 0.2 Mg CO_2e $ha^{-1}y^{-1}$) than in exposed abandoned ponds (30.6 ± 1.9 Mg CO_2e ha^{-1} y^{-1}) (Cameron et al., 2019); in other words, an increase in greenhouse gas emissions occurred when ponds were abandoned. Meanwhile, pond abandonment resulted in additional soil carbon stocks of 8.81 Mg C ha^{-1} in Sayung. This finding confirms the result of Cameron et al. (2019), indicating that inundated soils inhibit carbon oxidation. Inundation may be related to the RSLR value; as shown in Table 2 the RSLR in abandoned ponds was significantly higher in Sayung than Wedung.

4.2 Susceptibility of converted mangrove lands to relative sea-level rise

Studies on the vulnerability of various mangrove conditions to rising sea levels are increasing globally (Krauss et al., 2010; Lovelock et al., 2015; McKee and Vervaeke, 2018). However, this is the first assessment in Indonesia using rSET-MH. This study also includes other land-use types related to mangroves – working and abandoned ponds – to assess the potential future fate of current coastal land-use types. The study found that land-use change has promoted a reduction in land surface elevation. This may affect the vulnerability of coastal land to increasing sea levels. Mangroves appear to be the least susceptible to RSLR compared to working and abandoned ponds, as shown by the elevation surplus seen in

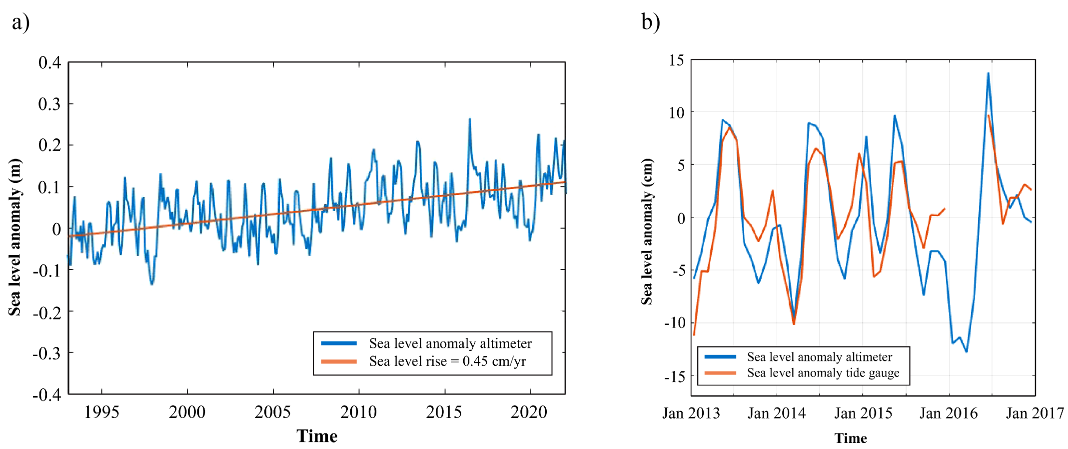

FIGURE 4
(a) The local sea-level trend from 1993 to 2022 in the Java Sea near Demak coast (cm yr^{-1}) and **(b)** comparison of sea-level anomaly trends taken from two datasets (altimeter satellite data from data.marine.copernicus.eu and tide gauge data from www.ioc-sealevelmonitoring.org).

TABLE 2 Relative sea-level rise and wetland relative sea-level rise in mangroves, working ponds, and abandoned ponds (mean ± standard error in cm yr^{-1}).

Region/Land-use type	Relative sea-level rise (cm yr^{-1})	Wetland relative sea-level rise (cm yr^{-1})
Wedung		
Mangroves	5.56 ± 1.65	(–) 2.02 ± 1.65
Working ponds	6.82 ± 5.48	6.44 ± 5.48
Abandoned ponds	1.36 ± 1.69	1.86 ± 1.69
Sayung		
Mangroves	8.00 ± 6.06	6.54 ± 6.06
Working ponds	10.39 ± 4.20	7.56 ± 4.20
Abandoned ponds	10.46 ± 3.22	15.00 ± 3.22

In wetland relative sea-level rise, negative and positive values show elevation surpluses and deficits, respectively.

Wedung mangroves, and the lowest elevation deficit in Sayung mangroves.

To maintain the long-term stability of coastal land, soil surface elevation gain must be equal to or higher than RSLR. Based on the rSET measurements, elevation gains were greater in Wedung and smaller in Sayung (Table 1) than what were observed over 3.5 years in degraded mangroves by Hanggara et al. (2021) in Percut District in North Sumatra (4.17 ± 2.40 cm yr^{-1}). This comparison suggests that in addition to different observation durations, site characteristics may affect the ability of mangroves to elevate their forest floor. Meanwhile, the sinking of all studied land-use types in Demak has coincided with a rising sea level (Figure 4). Estimated local SLR in Demak was higher than the global mean SLR (0.32 cm yr^{-1}) (Church and White, 2011). Assessment of RSLR in Demak's mangroves has been undertaken before by Van Bijsterveldt et al. (2023), who used water level measurements; this confirmed an increase in RSLR along the coast from north to south of Demak, similar to our RSLR estimates in mangroves we found in Wedung that had a lower RSLR value than Sayung (Table 2).

Comparing mangrove soil SEC with RSLR yielded an average elevation surplus in Wedung and an elevation deficit in Sayung (Table 2). This finding implies that mangroves in Wedung gained elevation more rapidly than the RSLR rate, but the opposite was true in Sayung. However, the fate of mangroves in Wedung could be different in future because the type of tide could change, along with rising sea levels (Krauss, 2021). Even though an elevation deficit was found in Sayung mangroves, they have not drowned immediately because the tidal range of this location is between 40 and 60 cm yr^{-1} (Smits, 2016; Tas et al., 2020). A previous study reported that elevation deficit in a coastal wetland having mean tidal range of 4 m would take around 1250 years to submerge (Krauss, 2021).

When compared to mangrove sites, soil SEC in working ponds was recorded to be smaller in Wedung but greater in Sayung (Table 1). The higher elevations found in working ponds in Sayung were mostly due to accretion. Floods occurred three times in 2022 (BPS, 2023); this could have carried in suspended sediment and hampered pond draining practices, thus preventing considerable amounts of sediment from being lost through outflow (Lal, 2017). Meanwhile, subsidence in working ponds was found to be greater than in mangroves (Table 1) likely because ponds had been subjected to compaction during their construction (Boyd et al., 2002). Comparison between SEC and RSLR revealed elevation deficits in working ponds in Wedung and Sayung (Table 2); these deficits appeared to be higher than in mangroves, indicating that working ponds are more vulnerable to RSLR.

Abandoned ponds in Wedung and Sayung had a declining trend for surface elevation, demonstrated by a negative SEC resulting from lower rates of accretion than subsidence (Table 1). The lower accretion seen in the abandoned ponds we studied could be due to tidal influence in these plots; limited access for the tide to affect landward abandoned ponds in Wedung might reduce the sediment supply, meanwhile, the plot positions of seaward abandoned ponds in Sayung were more susceptible to the stirring and movement of bottom sediments washed out to sea (Muskananfola et al., 2020). Compared to working ponds, subsidence in abandoned ponds was lower in Wedung but higher in Sayung (Table 1). Therefore, we see greater elevation deficit in abandoned ponds in Sayung (Table 2). This means that the abandoned ponds in Sayung were more susceptible to RSLR.

4.3 Scenarios to prevent the loss of soil carbon and surface elevation

This study showed various effects of mangrove-converted aquaculture and abandoned ponds on soil carbon stock and surface elevation dynamics. Other coastal areas worldwide prioritizing coastal management actions may therefore consider the following scenarios to increase soil carbon stocks and/or surface elevation.

1. Carbon enrichment

- Conversion of mangroves to aquaculture ponds in Wedung resulted in a gain in soil carbon stock. Increased soil carbon in working ponds was therefore likely influenced by allochthonous sources (such as input from the river) and/or autochthonous sources (such as accumulation of fecal matter). However, according to another study in Sawah Luhur Village, Banten, interior mangroves converted to sparse silvofishery ponds (40–50 cm in distance from other trees) resulted in a gain of soil carbon stocks of 6.80 Mg C ha^{-1} (Royna et al., 2024). Therefore, growing mangroves along pond embankments could perhaps help to enrich soil carbon in aquaculture areas compared to non-mangrove aquaculture. As there are limited studies of soil carbon stock changes in converted mangroves, the similar study could be replicated in different locations for a better understanding of the implications of this practice.
- The abandoned pond in Sayung offers valuable lessons on preventing soil carbon loss through inundation. Maintaining abandoned ponds in inundated conditions

might inhibit decomposition rates (Arifanti et al., 2019) and decelerate the oxidation process (Cameron et al., 2019), consequently preventing soil carbon stocks from being released into the atmosphere. As such, it is recommendable to leave abandoned ponds in an inundated condition to keep the carbon stored in the soil, rather than letting abandoned ponds become exposed.

2. Elevation enhancement

- A smaller difference in elevation deficit was found in Sayung when mangroves were changed to working ponds. The significant contribution that SAR makes to SEC in working ponds very likely originates from the coastal floods that have frequently occurred in Sayung (three times in 2022, compared to Wedung where no floods are recorded) (BPS, 2023). In a study conducted on a wetland associated with Rhône River in southern France, riverine floods promoted rapid sediment deposition, thus increasing sediment accretion at the wetlands (Hensel et al., 1999). Hence, surface elevation gain generated by floods cannot be relied upon to enhance soil SEC in working ponds, as floods are otherwise extremely detrimental to coastal communities living in Sayung (Van Bijsterveldt et al., 2023). Another way to elevate surface elevation in working ponds might be to integrate mangroves into the aquaculture system. A previous study reported that mangroves could strengthen pond embankments (Bosma et al., 2020) and reduce erosion, thereby minimizing significant elevation losses in working ponds.
- Differences in elevation deficit values were lower in Wedung when pond abandonment occurred. This is because the subsidence rate in abandoned ponds in Wedung was lower compared to those in Sayung, which aligns with research findings reported by Sarah et al. (2020). Their study found that the subsidence rate was smaller in the north rather than south of Demak due to mass groundwater extraction in Sayung (Aditiya and Ito, 2023). Controlling groundwater extraction may reduce the loss of soil surface elevation. Due to the limited number of studies on subsidence in abandoned ponds, further studies are required in the near future to address this information gap.

5 Conclusions

In Demak Regency, conversion of mangroves into aquaculture ponds, and the subsequent abandonment of these ponds, has resulted in changes in soil carbon stocks and surface elevation. Converting mangroves to aquaculture resulted in soil carbon stock gains in Wedung, but losses in Sayung. Meanwhile, pond abandonment caused a reduction of soil carbon stock in Wedung but an increase in soil carbon stock in Sayung. These two common practices (mangrove conversion and pond abandonment) showed contrasting results in terms of elevation change. When mangroves were converted to working ponds, the elevation surplus turned to elevation deficit in Wedung; while this practice triggered a slightly worse elevation deficit in Sayung. When working ponds became abandoned, this led to a small elevation deficit in Wedung, but a large deficit in Sayung. These increased elevation deficits make diverse land-use types more vulnerable to relative sea-level rise. From this case study in Wedung and Sayung, several scenarios emerged that offer potential to increase of soil carbon stocks or surface elevation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

TA: Conceptualization, Formal analysis, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. CK: Conceptualization, Supervision, Validation, Writing – review & editing. DB: Conceptualization, Supervision, Validation, Writing – review & editing. JR: Data curation, Validation, Writing – review & editing. PS: Visualization, Writing – review & editing. BH: Data curation, Validation, Writing – review & editing. YG: Writing – review & editing. MR: Data curation, Writing – review & editing. DM: Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer JJ declared a shared affiliation with the authors TA, CK, DB and DM to the handling editor at the time of review.

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Supplementary material

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