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Intertwined effects of climate and land use change on environmental dynamics and carbon accumulation in a mangrove-fringed coastal lagoon in Java, Indonesia

K. Anggi Hapsari[1] | Tim C. Jennerjahn[2,3] | Martin C. Lukas[4] | Volker Karius[5] | Hermann Behling[1]

[1]Department of Palynology and Climate Dynamics, University of Goettingen, Goettingen, Germany

[2]Department of Biogeochemistry and Geology, Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany

[3]Faculty of Geosciences, University of Bremen, Bremen, Germany

[4]Sustainability Research Center (artec), University of Bremen, MARUM – Center for Marine Environmental Sciences, Bremen, Germany

[5]Department of Sedimentology and Environmental Geology, Geoscience Center, University of Goettingen, Goettingen, Germany

Correspondence
K. Anggi Hapsari, Department of Palynology and Climate Dynamics, University of Goettingen, Goettingen, Germany.
Email: kartika.hapsari@biologie.uni-goettingen.de

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Abstract

The identification and quantification of natural carbon (C) sinks is critical to global climate change mitigation efforts. Tropical coastal wetlands are considered important in this context, yet knowledge of their dynamics and quantitative data are still scarce. In order to quantify the C accumulation rate and understand how it is influenced by land use and climate change, a palaeoecological study was conducted in the mangrove-fringed Segara Anakan Lagoon (SAL) in Java, Indonesia. A sediment core was age-dated and analyzed for its pollen and spore, elemental and biogeochemical compositions. The results indicate that environmental dynamics in the SAL and its C accumulation over the past 400 years were controlled mainly by climate oscillations and anthropogenic activities. The interaction of these two factors changed the lagoon's sediment supply and salinity, which consequently altered the organic matter composition and deposition in the lagoon. Four phases with varying climates were identified. While autochthonous mangrove C was a significant contributor to carbon accumulation in SAL sediments throughout all four phases, varying admixtures of terrestrial C from the hinterland also contributed, with natural mixed forest C predominating in the early phases and agriculture soil C predominating in the later phases. In this context, climate-related precipitation changes are an overarching control, as surface water transport through rivers serves as the "delivery agent" for the outcomes of the anthropogenic impact in the catchment area into the lagoon. Amongst mangrove-dominated ecosystems globally, the SAL is one of the most effective C sinks due to high mangrove carbon input in combination with a high allochthonous carbon input from anthropogenically enhanced sediment from the hinterland and increased preservation. Given the substantial C sequestration capacity of the SAL and other mangrove-fringed coastal lagoons, conservation and restoration of these ecosystems is vitally important for climate change mitigation.

KEYWORDS
carbon accumulation rate, climate change, estuary, land use change, mangrove, palaeoecology, watershed, XRF

1 | INTRODUCTION

Many coastal lagoons comprise very dynamic and highly productive wetland ecosystems that provide a wide range of ecosystem services including, for example, habitats for mangrove forests, salt marshes and aquatic biota, nutrient cycling, storm protection, fisheries, salt production, and tourism (Alongi, 2012; Anthony et al., 2009). Coastal lagoons are also important for the global carbon (C) cycle because of their high productivity and accretion rate (Brevik & Homburg, 2004; Chmura, Anisfield, Cahoon, & Lynch, 2003; Eong, 1993; Jennerjahn & Ittekkot, 2002; Twilley, Chen, & Hargis, 1992). Proportionally, coastal wetland ecosystems allocate more C below- than aboveground, in particular in their sediments (Alongi, 2012; Lovelock, 2008; Ouyang, Lee, & Connolly, 2017), highlighting the significance of belowground C storage in these ecosystems. However, quantitative data of belowground C storage are scarce (Donato et al., 2011; Ezcurra, Ezcurra, Garcillán, Costa, & Aburto-Oropeza, 2016), and understanding of the underlying dynamics is limited (Marchio, Savarese, Bovard, & Mitsch, 2016).

Coastal lagoons and the ecosystem services they provide are threatened by the effects of global environmental change, such as sea level rise, which can cause coastal erosion, extreme floods, destruction of coastal wetlands, and habitat loss for aquatic biota (Anthony et al., 2009). This will simultaneously affect the social and economic conditions of human societies (Silva, Katupotha, Amarasinghe, Manthrithilake, & Ariyaratna, 2013). Extensive anthropogenic pressures in coastal areas, such as land use change and natural resource exploitation, also threaten these ecosystems (Anthony et al., 2009; Silva et al., 2013). Mangrove ecosystems, which cover large expanses of tropical coastlines, are under threat mainly from human interventions, such as conversions to agriculture and aquaculture, land use changes and hydrological alterations in river catchments, timber harvesting, overexploitation of natural resources, and infrastructure construction (Chowdhury, Uchida, Chen, Osorio, & Yoder, 2017). Climate change may also negatively affect mangrove ecosystems and their carbon storage potential (Alongi, 2015; Jennerjahn et al., 2017). Mangrove forest area has been declining at rates of 1%–2% per year for a long time (Valiela, Bowen, & York, 2001). Although these rates have decreased substantially, losses remain alarmingly high in Southeast Asia (Richards & Friess, 2016). In Indonesia, mangrove forests have undergone an annual deforestation rate of 1.24%, an equivalent of 52,000 ha, per year since 1980. These lost mangrove forests could potentially absorb 0.07–0.2 Gt of C annually (Murdiyarso et al., 2015).

Humans are considered a major environmental force, as they have significantly modified biodiversity, climate, and natural cycles of for example, nutrients, water and carbon (Corlett, 2015; Raupach & Canadell, 2010). The term “Anthropocene” is used to refer to the current period where humans are seen as important as natural processes in shaping the planet (Corlett, 2015). The Anthropocene is characterized by the substantial increase in anthropogenic CO_2 emissions since the onset of industrialization (Raupach & Canadell, 2010), resulting in rapid climate warming and concomitant changes to the earth system, such as sea level rise, increased prevalence of extreme weather events, and food shortages (Huber & Gulledge, 2011; Marzeion, Cogley, Richter, & Parkes, 2014; Wheeler & von Braun, 2013).

As an effort to mitigate climate warming, a global political action plan was set in place to limit the global temperature increase to 2°C by reducing C emissions (UNFCCC, 2015). However, emission-cuts alone will not be sufficient to keep global warming below 2°C (Rau & Greene, 2015). Efforts to reduce atmospheric CO_2 through conservation, restoration, and improved land management need to be undertaken, which includes the identification and quantification of natural carbon sinks (Griscom et al., 2017).

The Segara Anakan Lagoon (SAL), the last large mangrove-fringed ecosystem on the Indonesian island of Java, is a coastal wetland system that is important for C sequestration, but that has been affected by intense human activities for centuries (Yuwono et al., 2007). The SAL’s biodiversity and ecosystem services, including its function as a habitat and nursery ground for aquatic biota, are threatened by land conversions to aquaculture/agriculture, mangrove extraction, and high levels of sedimentation and pollution (Jennerjahn & Yuwono, 2009; White, Martosubroto, & Sadorra, 1989; Yuwono et al., 2007).

Though the SAL is considered a “degraded” mangrove-fringed estuarine ecosystem, its soil organic carbon stocks are similar to those of some “undegraded” mangrove forests in Indonesia (Weiss et al., 2016). However, the dynamics and magnitude of carbon accumulation are not well understood, and the knowledge of longer term environmental dynamics is generally limited. Sedimentation, which has rapidly reduced the size of the lagoon, has been analyzed through shoreline change reconstruction going back to the mid-19th century (Lukas, 2014a, 2015a, 2017). Knowledge about the longer term sedimentation dynamics is nonexistent.

In this paper, we provide information on the historical environmental dynamics of the SAL over the past 400 years. Our research aimed to (a) quantify the C accumulation in lagoon sediment, (b) explain how climate and land use change affects lagoon dynamics and its C sequestration capacity, and (c) assess the significance of the C accumulation capacity of the SAL in comparison to other mangrove-dominated ecosystems.

2 | STUDY SITE

2.1 | Environmental setting

The Segara Anakan Lagoon is located on the southern coast of Java Island, west of the city of Cilacap (Figure 1). It is surrounded by around 9,200 ha of mangrove forest (Ardli & Wolff, 2009), which mainly consists of *Rhizophora apiculata*, *Avicennia corniculatum*, *A. alba*, *Nypa fruticans*, *Sonneratia caseolaris*, and *Bruguiera gymnorrhiza* (Hinrichs, Nordhaus, & Geist, 2009). The SAL catchment comprises an area of around 450,000 ha, with a plain to hilly central river basin, volcanic mountains in the northwest, and sedimentary mountain ranges in the south and northeast (Lukas, 2015b, 2017).

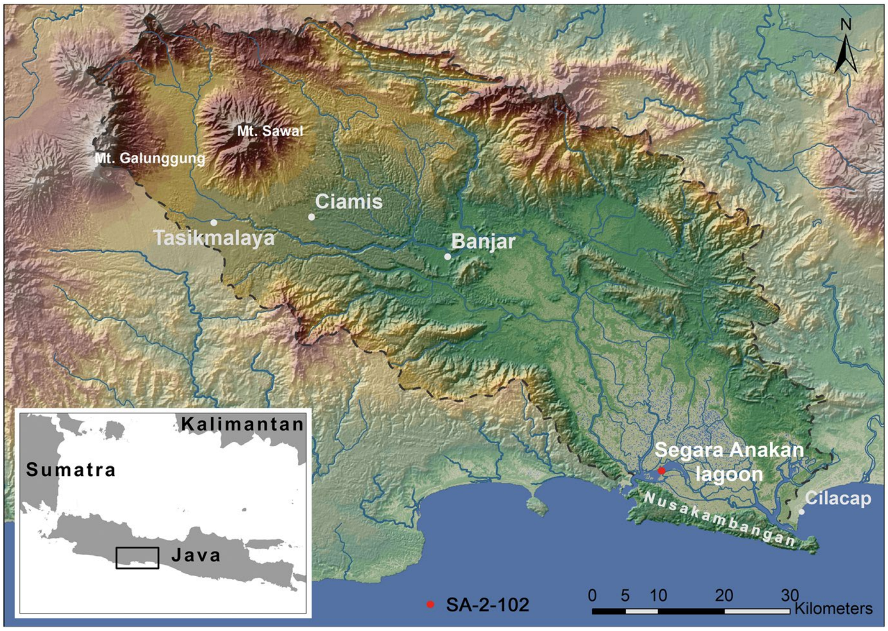

FIGURE 1 Map of the Segara Anakan Lagoon and its catchment area. The Segara Anakan Lagoon's watershed is marked with dashed lines

The SAL is separated from the Indian Ocean by the rocky, mountainous Nusakambangan Island and is connected to the ocean via two channels: one to the west and one to the east of Nusakambangan. Lagoon salinity (reported in practical salinity units [psu]) ranges from 1 to 28 depending on freshwater input and rainfall seasonality (Holtermann, Burchard, & Jennerjahn, 2009; Noegrahati & Narsito, 2007; White et al., 1989). The salinity fluctuation is strongly influenced by freshwater input from the Citanduy River, which contributes about 80% of the freshwater discharge into the SAL with a range of 78–300 m^3/s (average 140 m^3/s; Holtermann et al., 2009). A minor contribution of freshwater input comes from several smaller rivers, such as the Cibereum and Cikonde.

The tides within the SAL are semidiurnal with an amplitude ranging from 0.2 to 2.6 m (White et al., 1989). The climate in the lagoon area is tropical humid with a mean annual temperature of 27.2°C and little variation throughout the year. The mean annual precipitation is 3,400 mm, with drier conditions from July to September, wetter conditions from October to May, and peak rainfall in November (www.weatherbase.com). The interannual rainfall variability in this area is influenced by the El Niño Southern Oscillation (ENSO; Qian, Robertson, & Moron, 2010).

2.2 | Land use change in the Segara Anakan Lagoon and its hinterland

"Segara Anakan" is loosely translated as "child of the sea." The lagoon is inhabited by c. 17,300 "Orang Laut" ("people of the sea") who live in the four villages of Kampung Laut ("sea village"): Ujungalang, Ujunggagak, Klaces, and Penikel (BPS Cilacap, 2017). Most residents of Kampung Laut are fishers and farmers. In recent decades, farming and aquaculture have increased in popularity relative to fishing as sedimentation has turned substantial parts of the lagoon into land (Ardli & Wolff, 2009; BPS Cilacap, 2017; Heyde, 2016; Olive, 1998). Descendants of guards from the Mataram kingdom, the predecessors of the Orang Laut, have populated the SAL at least since 1705 (Mulyadi, 2013; Schwerdtner Máñez, 2010; Waryono, 2002). In 1724, nine villages were documented in the SAL by Francois Valentijn, a Dutch minister and naturalist (Mulyadi, 2013; Schwerdtner Máñez, 2010). The population of Kampung Laut has risen over time, with some phases of particularly rapid growth, such as the period 1924–1939 when the number of residents doubled from 680 to 1,300 (Waryono, 2002).

According to historical records, the Dutch began subjecting the SAL to pearl exploitation around 1699 (Schwerdtner Máñez, 2010). Documentations of mangrove deforestation go back to the second half of the 19th century. Between the 1870s and 1930s, rising fuelwood and charcoal demands of sugar factories and railway companies by far exceeded local lagoon residents' timber demands for houses and fishing stakes. This triggered extensive wood extraction, rendering management attempts of the colonial forest administration ineffective (de Haan, 1931).

Over the course of the 20th century, a substantial proportion of the mangrove and swamp forest areas surrounding the SAL and the lower river basin further upstream were converted into settlements, rice fields, and aquaculture ponds as a result of government-initiated resettlement and agricultural development projects and individual settlers moving in from other parts of Java (Ardli & Wolff, 2009; Irwansyah, 2010; Lukas, 2014b, 2017; Olive, 1998). By the 1970s, the area of mangrove forest converted to settlements and agricultural land was estimated to be eight times (c. 1,100 ha) larger than in the 1940s (c. 140 ha; Irwansyah, 2010). Between 1968 and 1987, an additional 10,000 ha of mangrove forest was converted into rice fields (Irwansyah, 2010; Olive, 1998). Today, much of the remaining mangrove forest area is degraded. Tenure conflicts and mismatches between government planning and the perceptions, claims, and practices of local residents on the ground impair mangrove reforestation efforts (Heyde, 2016).

The hinterland of the SAL, which comprises the catchments of the Citanduy, Cibeureum, and Cikonde Rivers, has also experienced a long history of land use change. In the early 18th century, the peasants of the former Priangan Regency, to which considerable sections of the lagoon's catchment belonged to, started to shift from swidden agriculture (locally called *ngahuma*), to permanently irrigated rice farming (*sawah*; Herayati, Masnia, & Haryanti, 1993). This agricultural system was already introduced by people from the Mataram kingdom during their reign in Priangan from 1620 to 1705 (Herayati et al., 1993; Muhzin, 2008). Compulsory coffee cultivation under the colonial regime, excessive timber extraction, plantation development, and in-migration considerably reduced forest cover in the catchment of the SAL in the 19th and early 20th centuries (Lukas, 2017). As in the whole of Java, there was considerable expansion of rainfed and irrigated agriculture, particularly in the late 19th and early 20th centuries (Boomgaard & van Zanden, 1990; Smiet, 1990; van der Eng, 2008). The arable land area in Java increased from approximately 2.1 million hectares in 1880 to approximately 4.2 million hectares in 1915 (Boomgaard & van Zanden, 1990). In the catchment of the SAL, the expansion of both irrigated and rainfed agricultural land continued until the 1990s (Lukas, 2015b, 2017).

Most of the remaining forests were converted into monocultural production forests under the colonial Forest Service and its successor organization (Lukas, 2015b; Peluso, 1992). Today, more than one-fifth of the total land area of Java is formally under the control of the state forest corporation. About 50% of these lands are planted with teak (*Tectona grandis*), while 36% are planted with pine (Perum Perhutani, 2016). These two species also dominate most state forest lands in the catchment of the SAL (Lukas, 2015b). The pine species (*Pinus merkusii*) is not native to the island of Java but was introduced from Sumatra and planted for the purpose of resin production beginning in the 1920s/1930s (Becking, 1935; Fitriani, 2012).

Along with the land use changes described above, forest management practices, conflicts over state forest and plantation lands, as well as erosion and mass movements from roads, trails, and settlements, all contributed to increased river sediment loads and lagoon sedimentation from the late 19th and throughout the 20th centuries (Lukas, 2015b, 2017). "Ngaguguntur" (the digging back of hill slopes to expand agricultural land and shoveling the excavated soil into streams and rivers), agriculture in riparian zones, and river bank erosion have also contributed to high river sediment loads (Diemont, Smiet, & Nurdin, 1991; Lukas, 2017). Furthermore, the reclamation of the swamp forests and extensive river straightening and embankments in the lower river basin upstream of the SAL for agriculture and settlements, which began in the first three decades of the 20th century and which were pushed forward in the frame of river and agricultural development projects in the 1970s and 1980s, have contributed to sedimentation of the SAL through enhancing sediment transport (Lukas, 2015b, 2017). A floodway and a river diversion constructed in the frame of these projects in the 1970s/1980s had similar effects (Lukas, 2017).

3 | MATERIALS AND METHODS

3.1 | Sediment core

In 2014, a 500 cm long sediment core (SA-2-102; 7°40′S 108°49′E; Figure 1) was recovered from the center of the SAL using a 5 cm diameter Livingstone piston corer (Wright, 1967). A short replicate core (100 cm) was taken c. 20 cm away from the SA-2-102 borehole, because the lower half of the first meter (67–100 cm) of the initial core was lost.

3.2 | Sediment dating (^{210}Pb and AMS radiocarbon dating)

The top 270 cm of the SA-2-102 core (samples from depths 60–100 cm were taken from the replicate core) were analyzed for ^{137}Cs, ^{210}Pb, and ^{214}Pb at the Laboratory for Radioisotopes (ISOLAB) in Goettingen, Germany. The samples were sliced into increments of 10 cm, dried, and ground. Samples were then packed in sealed plastic tins (c. 35 cm^3) and left to rest for at least 3 weeks prior to measurement to establish equilibrium between ^{226}Ra and ^{214}Bi (Goodbred & Kuehl, 1998). Gamma-ray measurements of ^{137}Cs (661.7 keV), ^{210}Pb (46.6 keV), and ^{214}Pb (295.2 and 351.9 keV) were performed on each sample using three low background Ge(Li) detectors for 250,000 s (2.9 days). Three bulk samples were selected from between 270 and 500 cm of the SA-2-102 core and measured using *Accelerator Mass Spectrometry (AMS) radiocarbon analysis* at the National Taiwan University (NTU) AMS-Laboratory, Taiwan (Table 1).

TABLE 1 AMS-^{14}C results of core SA-2-102

Depth (cm)	Sample code	Material	^{14}C age	Calibrated age (2σ)	Posterior probability (outlier analysis[a])
228	*SA102-3*	*Plant remains*	*F14C 1.005 ± 0.0001*		*100*
437	SA102-2	Plant remains	112 ± 1	1816–1922 AD	10
499	SA102-1	Bulk sediment (~2 cm^3)	385 ± 2	1480–1624 AD	15

Note: Outlier is in italic.

[a]Using SSimple model (Christen, 1994) in OxCal (Ramsey, 2009).

3.3 | Pollen and spores analysis

Plant communities are largely shaped by climate and environmental conditions (Franklin, Serra-Diaz, Syphard, & Regan, 2016). Thus, identifying past vegetation and how it shifted through time can reveal past changes in climatic and/or environmental conditions (Nolan et al., 2018). Palynology, or the analysis of pollen and spores, is widely used to reconstruct past vegetation compositions (Nolan et al., 2018).

To assess past vegetation composition in the SAL area and its hinterland, 30 subsamples of 2 cm^3 each were taken from the SA-2-102 core and processed for pollen analysis following standard extraction methods (Faegri & Iversen, 1989). One tablet of *Lycopodium* spores was added to each subsample prior to the pollen extraction process. Pollen and spores were identified using the reference collection of pollen and spores of the Department of Palynology and Climate Dynamics, University of Goettingen, and other available references (e.g., Pollen and Spore Image Database of the University of Goettingen-available at http://gdvh.uni-goettingen.de/; Li et al., 2012; Mao et al., 2012; Mildenhall & Brown, 1987; Poliakova & Behling, 2016). Due to the poor pollen preservation, pollen and spores were counted up to a sum of 200 pollen grains for each sample. Pollen concentration was calculated as grains/cm^3 based on the total grains of pollen counted, whereas spore concentration was calculated as grains/cm^3 based on the total grains of pollen and spores counted. The pollen taxa were then classified into five groups according to the ecological characteristics or the function of the source plants (e.g., Giesen, Wulffraat, Zieren, & Scholten, 2007; Mao et al., 2012; Ni, Yu, Harrison, & Prentice, 2010; Sosef, Hong, & Prawirohatmodjo, 1998; Wang, Mu, Li, Lin, & Wang, 2011). These groups are: (a) mangrove and mangrove associates (MMA), which represent the group of taxa that grow exclusively in mangrove areas and the associated plants; (b) mixed forest (MXF), which represents the vegetation making up coastal, riparian, lowland and montane forests; (c) open vegetation (OV), which represents the taxa that commonly grow in nonforested areas that never supported the forest or resulted from disturbance such as forest clearing or conversion; (d) staple agriculture (SA), which represent the taxa cultivated for staple food and the plants that grow on cultivated land; and (e) exotic taxa (EX), which represent introduced or non-native taxa.

3.4 | XRF scanning and biogeochemical analysis

In order to trace changes in environmental conditions of the SAL, XRF scanning and analysis of total organic carbon (C_{org}), total nitrogen (N), and the stable isotope composition of organic carbon ($\delta^{13}C_{org}$) were conducted. The XRF scanning of core SA-2-102 was performed at the Geomorphological-Sedimentological Laboratory of the Geomorphology and Polar Research (GEOPOLAR), University of Bremen. The sediment core was transferred to the U-channel and scanned on the ITRAX (CS-8)-XRF scanner with Molybdenum-(Mo)-tube (Croudace, Rindby, & Rothwell, 2006). XRF scanning was conducted at 30 kV and 10 mA at 1 mm resolution with 10 s exposure time. The XRF counts of the detected elements (e.g., titanium [Ti], calcium [Ca], chlorine [Cl], sulfur [S], potassium [K], and bromine [Br]) were normalized against the scattering coherent (coh) peaks of Mo (Hahn, Kliem, Oehlerich, Ohlendorf, & Zolitschka, 2014). The data were reduced by calculating average values for 1 cm intervals.

C_{org}, N, and $\delta^{13}C_{org}$ of core SA-2-102 were determined by analyzing 45 subsamples (@ 2 cm^3) that were dried at 60°C and finely ground before analysis. C_{org} and N were determined by high temperature oxidation in a Euro EA3000 elemental analyzer. The analytical precisions for C_{org} and N were ±0.03% and ±0.01%, respectively.

Samples for C_{org} determination were treated using 1N HCl prior to analysis to remove carbonates. A similarly treated sample was used for determination of $\delta^{13}C_{org}$ in a Thermo Finnigan Delta Plus gas isotope ratio mass spectrometer after high temperature combustion in a Flash 1,112 EA elemental analyzer. $\delta^{13}C_{org}$ measurements are reported in standard δ-notation [$\delta = R_{sample}/R_{standard} - 1$, where R is the isotope ratio ($^{13}C/^{12}C$) in the sample or international standard Vienna Pee Dee Belemnite (VPDB)] in units of per mil (‰). Measurement uncertainty never exceeded ±0.1‰.

3.5 | Carbon accumulation rate

The C accumulation rate (CAR) of SA-2-102 was calculated by multiplying the sediment bulk density (BD) with C_{org} and the sediment accumulation rate produced by the age–depth model (Section 4.1). The CAR is displayed as g C m^{-2} $year^{-1}$. BD was calculated as the dry weight (g) divided by the wet sample volume (cm^3). Subsamples of 2 cm^3 were taken along SA-2-102 core at 5 cm intervals and subsequently dried at 105°C for 24 hr to calculate the sediment dry weight.

4 | RESULTS

4.1 | Lithology and age control

Both SA-2-102 and the replicate core consist mainly of silt and clay material without a clear indication of changing sediment composition (Figure 2). The unsupported ^{210}Pb activity of the core shows an irregular decrease that suggests an inconsistent sedimentation rate over time (Figure 2). Considering these circumstances, the use of a constant initial concentration (CIC) model for age calculation is not appropriate. The CIC model can only be applied when the activity of unsupported ^{210}Pb declines exponentially with depth (Appleby, 2008; Appleby & Oldfield, 1983). Therefore, a constant rate of supply (CRS) model was chosen to calculate the age (Appleby and Oldfield, 1978; 1983).

The CRS model, which assumes that the atmospheric deposition of excess ^{210}Pb is constant over time, is applicable for sediment cores with a nonmonotonic ^{210}Pb profile (Appleby, 2008; Applebl & Oldfield, 1978, 1983). Moreover, CRS is widely used and considered to be more

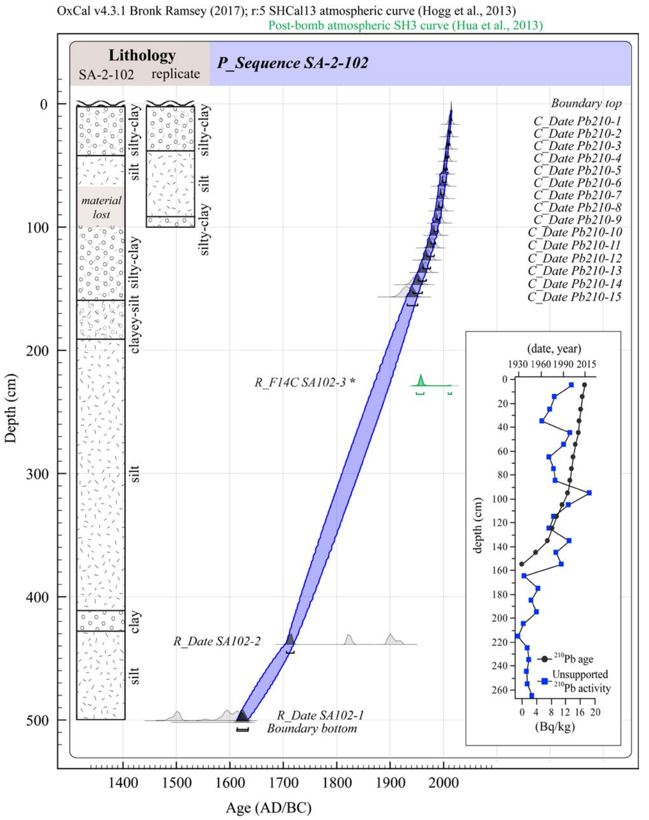

FIGURE 2 Lithology and age–depth model of cores taken from the Segara Anakan Lagoon. The age–depth model was constructed using the P-sequence in OxCal v 4.3.1 (Ramsey, 2009) and the initial ShCal.13 and PostBomb calibration curves (Hogg et al., 2013; Hua, Barbetti, & Rakowski, 2013). The unsupported ^{210}Pb activity and ^{210}Pb dates are presented in the inset. An outlier date is marked with an asterisk (*)

suitable to calculate ^{210}Pb dates in lakes, coastal zones or estuaries where sedimentation processes are highly influenced by anthropogenic activities (Appleby & Oldfield, 1978; Lubis, 2006). An independent tracer such as ^{137}Cs is often used to confirm the ^{210}Pb dates of the CRS model. However, in our case the ^{137}Cs values from both SA-2-102 and the replicate core were constantly below the detection limit.

The calendar dates produced from the CRS model (Table 2) are subsequently integrated with AMS ^{14}C dates to construct an age–depth model for the whole SA-2-102 core. The age–depth model was constructed using the P-sequence depositional model in OxCal v.4.3.1 (Ramsey, 2009) with a *k* value of 1. Prior to construction of the age–depth model, an outlier detection was conducted using the SSimple model (Christen, 1994) in OxCal. Sample SA102-3 was flagged as an outlier for its high posterior probability and was therefore excluded from the age–depth model (Table 1). The discrepancy of sample SA102-3 might be attributable to bioturbation, which possibly moved the sample from its correct stratigraphic position. The dates produced from this analysis are expressed as anno Domini/before Christ (AD/BC) and applied throughout the paper. The age–depth model indicates that core SA-2-102 spans a time period of around 400 years from 1620 to 2014 (Figure 2).

TABLE 2 ^{210}Pb dates of Segara Anakan core based on constant rate of supply model

Depth (cm)	Unsupported ^{210}Pb activity (Bq/kg)	Uncertainty (Bq/kg)	Calendar year (AD)	Posterior probability (outlier analysis[a])
0	13.7	3.0	2014 ± 3	10
10	9.0	3.0	2011 ± 3	10
20	7.6	2.9	2009 ± 3	10
30	5.5	2.9	2007 ± 3	10
40	13.2	3.0	2006 ± 3	10
50	11.5	2.9	2002 ± 3	10
60	7.4	2.9	1999 ± 4	10
70	8.7	3.0	1996 ± 4	10
80	9.1	2.8	1994 ± 4	10
90	18.4	3.0	1991 ± 4	10
100	12.8	2.9	1984 ± 4	10
120	7.4	2.9	1977 ± 5	10
110	8.8	2.9	1970 ± 5	10
130	13.0	2.9	1964 ± 5	10
140	9.5	2.9	1948 ± 7	10
150	10.9	2.9	1929 ± 9	10
160	0.7	2.6		
170	4.5	2.8		
180	2.6	2.7		
190	4.0	2.7		
200	0.4	2.5		
210	−0.9	2.5		
220	1.5	2.5		
230	2.0	2.5		
240	1.2	2.5		
250	1.5	2.6		
260	2.8	2.5		

[a]Using SSimple model (Christen, 1994) in OxCal (Ramsey, 2009).

4.2 | Pollen analysis, XRF, and biogeochemical analysis

Detailed results of pollen, XRF and biogeochemical analyses are provided in Table 3. The pollen record of SAL is divided into five palynological zones with two subdivisions in zone II (Figure 3) based on agglomeration in a constrained cluster analysis (CONISS; Supplementary S2; Grimm, 1987). The same zonation is used to divide the results of XRF scanning, biogeochemical analyses, and the calculation of C accumulation.

Zones I, II, and IV are dominated by the MMA (mangroves and mangrove associates) pollen group, while zones III and V are dominated by SA (staple agriculture). The proportions of pollen groups MXF (mixed forest) and OV (open vegetation) are relatively stable throughout the record with a higher MXF proportion in zone IV, and

TABLE 3 Results of pollen analysis, XRF scanning, and biogeochemical analysis

Zonation (depth and age)	Pollen analyses[a] (Figure 3)	XRF profile (Figure 4)	Biogeochemical analysis (Figures 4 and 5; C_{org})
SA-I 500–486 cm 1620–1640	56% MMA (e.g., *Rhizophora*, *Nypa*, *Bruguiera*, and *Avicennia*); 5% SA (e.g., *Oryza*-type, Colocasia, and Solanaceae); 6% OV (e.g., wild Poaceae and Asteraceae); 33% MXF (e.g., Moraceae–Urticaceae, Arecaceae, *Nauclea*, *Pometia*, and *Podocarpus*); 0% EX (*Pinus*)	Cl exponentially decrease toward present time Ti/Ca exponentially increases toward present time	C_{org} (1.6%) C_{org}N (12) $\delta^{13}C_{org}$ (−26.7‰)
SA-IIa 435–486 cm 1640–1700	50% MMA (▾); 7% SA (▴); 18% OV (▴); 25% MXF (▾); 0% EX (↔)		
SA-IIb 335–435 cm 1700–1790	45% MMA (▾); 12% SA (▴); 18% OV (↔); 25% MXF (↔); 0% EX (↔)		C_{org} (1.5%;▾) C_{org}N (10; ▾) $\delta^{13}C_{org}$ (−25.3‰; ▴)
SA-III 295–335 cm 1790–1830	18% MMA (▾); 35% SA (▴); 24% OV (▴); 19% MXF (▾); 4% EX (▴)		C_{org} (1%;▾) C_{org}N (7; ▾) $\delta^{13}C_{org}$ (−25.7‰; ▾)
SA-IV 295–190 cm 1830–1910	49% MMA (▴); 5% SA (▾); 11% OV (▾); 35% MXF (▴); 0% EX (▾)	Cl (▴) Ti/Ca (▾)	C_{org} (2.1%;▴) C_{org}N (16; ▴) $\delta^{13}C_{org}$ (−27.7‰; ▾)
SA-V 190–0 cm 1910–2014	24% MMA (▾); 27% SA (▴); 20% OV (▴); 23% MXF (▾); 6% EX (▴)	Cl (▾) Ti/Ca (▴)	C_{org} (1.2%; ▾) C_{org}N (9; ▾) $\delta^{13}C_{org}$ (−25.7‰; ▴)

Note: Values presented are averages.

▴, value increase; ▾, value decrease; ↔, value stable.

[a]Pollen group abbreviation (see Section 3.3).

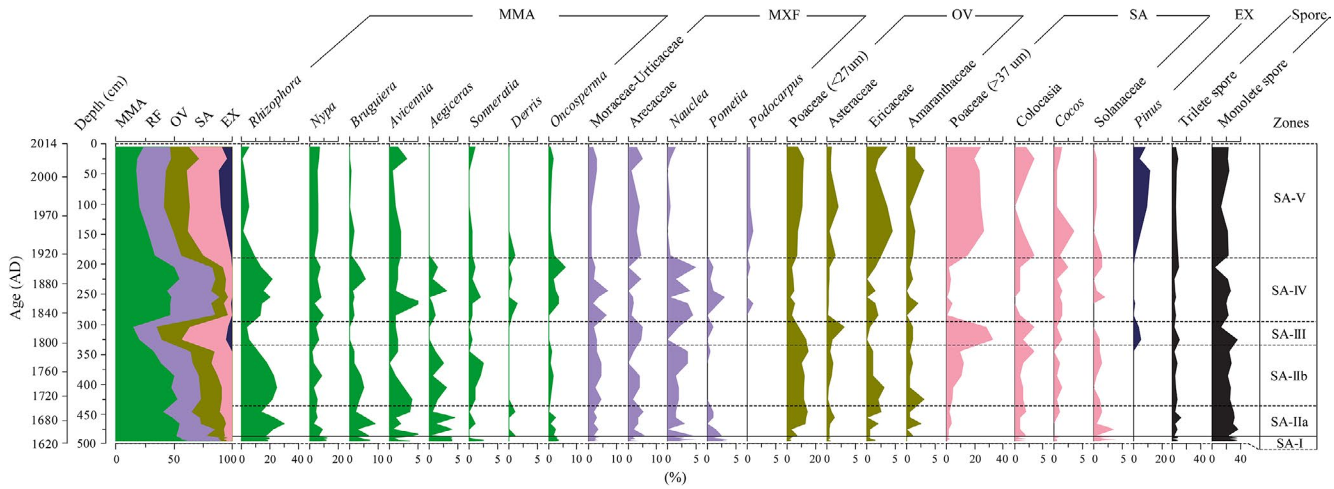

FIGURE 3 Pollen diagram of the Segara Anakan Lagoon core. Pollen were classified into five groups as follows: MMA: mangrove and mangrove associate; MXF: mixed forest; OV: open vegetation; SA: staple agriculture; and EX: exotic species. Selected taxa are shown. Complete list of taxa is provided in Supplementary S1

a lower OV proportion in zones I and IV. The pollen group EX (exotic species) is found in insignificant quantities throughout the record.

The results of XRF scanning are shown as element count per second (cps) at each measuring point. Selected elements demonstrating notable changes are reported in Figure 4 (Cl and Ti/Ca) and Supplementary S3 (S, K, and Br). The N values are relatively stable throughout the record (0.11%; Supplementary S3), while the C_{org} values fluctuate from 0.9% to 2.9%, with higher values in zone IV (Figure 4). Consequently, the C_{org}/N ratio is also higher in zone IV. The $\delta^{13}C_{org}$ values fluctuate from −22 to −28‰ (average −26.7‰) throughout the record, with lower values in zones IIa and IV (Figure 4).

4.3 | Carbon accumulation rate

The BD values are relatively stable throughout the SA-2-102 core, ranging from 0.5 to 0.9 g/cm^3 (average 0.7 g/cm^3; Figure 5). The average sediment accumulation rate over the entire period is 1.6 cm/year

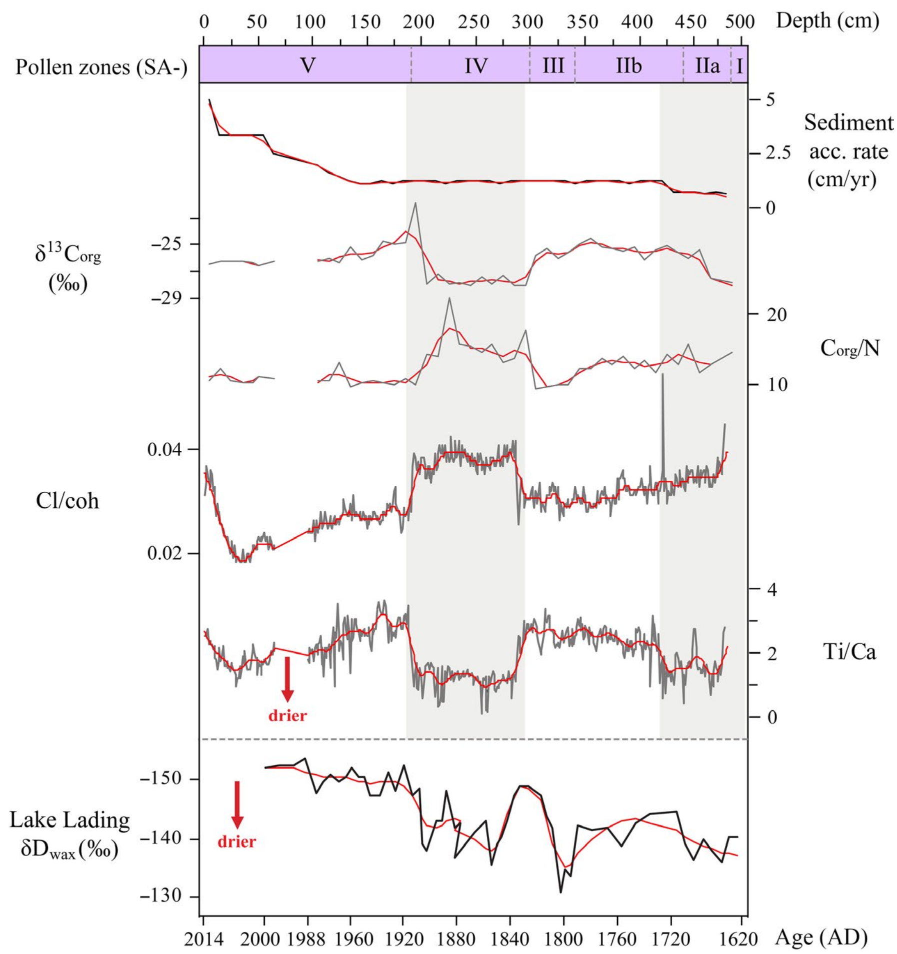

FIGURE 4 Records of sediment accumulation rate, $\delta^{13}C_{org}$, C_{org}/N, Cl, and Ti/Ca of the Segara Anakan Lagoon compared with the δD_{wax} record of Lake Lading in East Java (Konecky et al., 2003). The correlation between Ti/Ca from the SAL and δD_{wax} from Lake Lading is relatively strong and significant (r = −.55; p-value 9.435e-06; Supplementary S5). The gray bars highlight the periods of lower precipitation in the Segara Anakan and its catchment area as indicated by the Ti/Ca ratio

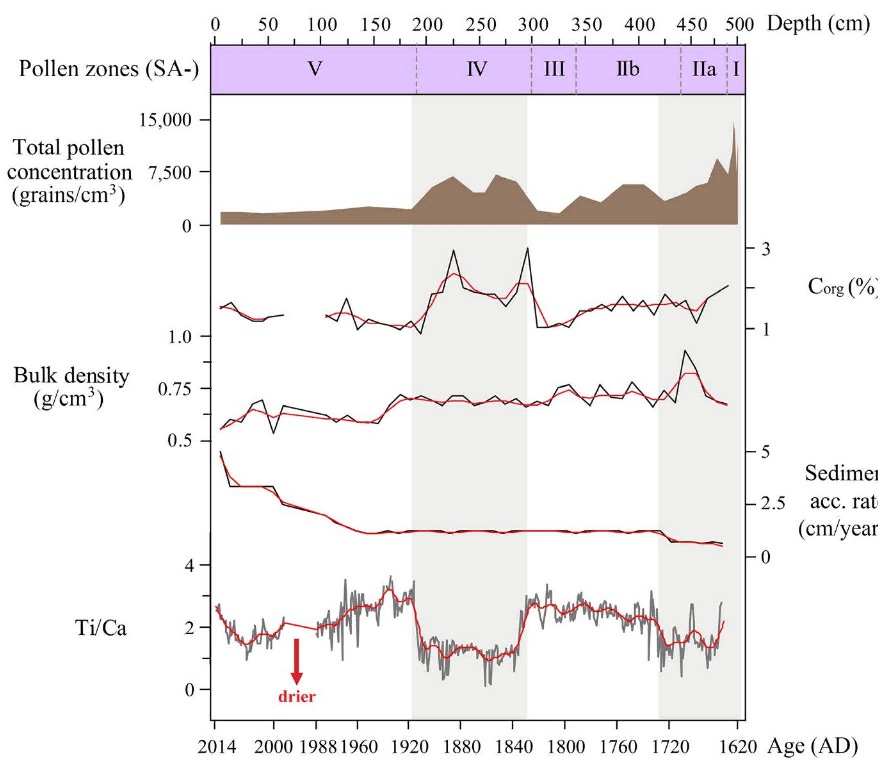

FIGURE 5 Total pollen concentration, C_{org} content, bulk density, and sediment accumulation rate of the Segara Anakan Lagoon core. The gray bars highlight the periods of lower precipitation in the Segara Anakan and its catchment area as indicated by Ti/Ca

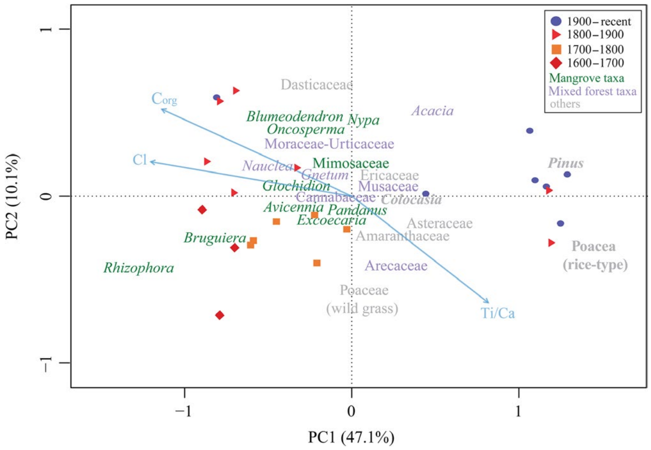

FIGURE 6 Principal component analysis (PCA) 1 and 2 for pollen data of the Segara Anakan Lagoon core. The mangrove taxa and its associates are in green, while mixed forest and other taxa are in purple and gray, respectively. The vectors for C accumulation, C_{org} (%), Ti/Ca and seawater/salt elements (Cl) are represented by blue arrows radiating from the center

(range 0.7–5 cm/year) with a minimum in Zone I and IIa (0.7 cm/year) and a maximum in Zone V (2.2 cm/year; Figure 5). The average CAR for the entire record is 126 g C m^{-2} $year^{-1}$, with a range of 5–370 g C m^{-2} $year^{-1}$.

The C_{org} content of SAL sediments varies over time (Figure 5). In order to identify the underlying causes of this variation, a principal component analysis (PCA) was performed on the records of C_{org}, pollen assemblages, and other environmental proxies (Ti/Ca and Cl). The first component (PC1; Figure 6) accounts for 47.1% of the total variance observed across the sample and separates mangrove and mixed forest taxa from other taxa identified from the pollen sample. The second component (PC2; Figure 6) accounts for only 10.1% of the total variance and likely indicates the periods before and after the introduction of exotic species (*Pinus*; Figure 3). The PCA result shows that the C_{org} percentage in SAL sediments is positively correlated with the abundance of mangrove taxa and its associates, including mixed forest taxa and the seawater/salt element (Cl), and it exhibits a strong negative correlation with the Ti/Ca ratio (Figure 6).

5 | DISCUSSION

5.1 | Segara Anakan Lagoon dynamics

Based on the evaluation of our combined datasets, four phases with variations in climate and land use/cover were identified.

5.1.1 | The rather dry “natural” period 1620–1730 AD

The sediment Ti/Ca ratio is a commonly used indicator in paleo reconstruction studies of rainfall and terrestrial sediment input (e.g., Mohtadi et al., 2011; Steinke et al., 2014). The low Ti/Ca ratio in the SAL sediment during the period 1620–1730 (Figure 4) indicates lower precipitation, which limited surface runoff and freshwater discharge from the river. Consequently, the sediment transport from the catchment area and, hence, the sediment accumulation rate in the Segara Anakan lagoon was low during this period. This is corroborated by a high sedimentary content of major seawater elements, Cl, K, S, and Br (Figure 4; Supplementary S3; Burton, Holman, Lazonby, Pillin, & Waddington, 2000; Haenssler, Unkel, Dörfler, & Nadeau, 2014), indicating a higher salinity due to lower freshwater input.

Pollen abundance and composition analysis revealed that the vegetation around the SAL and in its catchment area was dominated by mangrove forest during this period, with the dominant species being *Rhizophora*, *Bruguiera*, *Avicennia*, *Aegiceras* and *Nypa*, and mixed forest taxa (Figure 3; Supplementary S4). The domination of mangrove ($\delta^{13}C_{org}$ range −28 to −25‰; Rodelli, Gearing, Gearing, Marshall, & Sasekumar, 1984) and deciduous forest ($\delta^{13}C_{org}$ range −38 to −26‰; Ometto et al., 2006) vegetation is also confirmed by an average $\delta^{13}C_{org}$ of −26.7‰. A rather “natural” environmental condition, as indicated by the dominance of mangrove and mixed forest vegetation, likely minimized erosion in the catchment and hence limited sediment input into the SAL during this period.

5.1.2 | The wet period with increasing human use 1730–1830 AD

After 1730, an increase in the Ti/Ca ratio and the sedimentation rate was accompanied by a decrease of Cl, K, S, and Br content (Figure 4; Supplementary S3), indicating higher precipitation which resulted in higher freshwater and sediment input from the catchment and lower salinity in the lagoon. This is corroborated by a historical record of pearl fishing in the SAL, stating that an “unseasonal rainfall killed the young oyster” around 1730 (Schwerdtner Máñez, 2010 and references therein). From 1730 onward, the proportion of wild Poaceae, Ericaceae, and Amaranthaceae, as well as cultivated Poaceae pollen (e.g., *Oryza*, *Sorghum*, *Saccharum*, *Panicum*, *Setaria*) increased, while the proportion of mangrove pollen decreased (Figure 3; Table 3). These changes are corroborated by similar trends in the pollen concentration of the aforementioned taxa (Supplementary S4) and a higher $\delta^{13}C_{org}$ value, which indicates an admixture of C4 plants to the deposited organic matter (OM; França et al., 2013; Meyers, 1994; Figure 4).

Considering that the SAL was already inhabited by "Orang Laut" at that time (Section 2.2), the decline in mangrove forest pollen during this period might be related to mangrove forest utilization. The residents of Kampung Laut utilized mangrove wood mainly for home construction (Mulyadi, 2013; Waryono, 2002). The increase of cultivated Poaceae in the pollen record throughout the 18th century (Figure 3; Table 3) likely reflects the onset of larger scale anthropogenic land use in the lagoon's catchment area (Section 2.2).

The first occurrence of pine pollen (*Pinus* sp.) in the sediment record during the early 19th century (Figure 3) does not correspond to historical forestry records, which report that pine was introduced from Sumatra as part of a series of small-scale trials in the 1920s and then planted on a larger scale in the 1930s (Becking, 1935; Fitriani, 2012). Our pollen record indicates that pine could have been introduced to Java as a forest species earlier, or that the pine pollen was transported into the Segara Anakan catchment area by wind and subsequently transported via the river into the lagoon. The bisaccate morphology of *Pinus* pollen allows for long distance wind transport (c. 300 km; Reitz & Shackley, 2012; Twiddle, Jones, Caseldine, & Sugita, 2012).

5.1.3 | The drought period 1830–1910 AD

The lower Ti/Ca ratio and higher Cl, K, S, and Br values (Figure 4; Supplementary S3) indicate a period of lower precipitation in the SAL region and higher salinity in the lagoon between 1830 and 1910. This corresponds to a period of drier climatic conditions detected in the sediment record of Lake Lading, East Java, which is indicated by a higher δD_{wax} of terrestrial plant wax compounds during that time (Konecky et al., 2013). Both records suggest a widespread and strong drought across Java during this period, which is also reflected by the documentation of drought-related crop failures in the following periods: 1832–1836, 1844–1848, 1849–1851, 1858–1862, 1877–1888, and 1900–1902 (Boomgaard, 2002; Creutzberg & van Laanen, 1987; Fernando, 2010; van der Eng, 2010).

During this period, the $\delta^{13}C_{org}$ value decreased to an average of −27.7‰ and the C_{org}/N ratio increased to 16, suggesting less admixture of OM from nonwoody vegetation (Meyers, 1994). This is corroborated by a higher proportion of mangrove (e.g., *Rhizophora*, *Bruguiera*, and *Avicennia*) and mixed forest (e.g., *Nauclea*, Moraceae-Urticaceae, and *Pometia*) pollen and a lower proportion of cultivated Poaceae and *Pinus* pollen (Figure 3). Total pollen concentrations in absolute terms increased for most taxa during the 1830–1910 drought period, with the exceptions of wild grass and cultivated Poaceae (>37 µm; Figure 5; Supplementary S4).

Based on the common assumption that the pollen-spore assemblage in the sediment reflects the surrounding vegetation at the time of their deposition (Bradley, 1999), the pollen record would indicate an expansion of mangrove forest and mixed forest surrounding the lagoon or a reduction in agriculture. However, in interpreting pollen assemblages, attention needs to be paid to the various processes which may affect the transformation of plant communities into pollen assemblages, including variations in pollen deposition dynamics (Goring, Lacourse, Pellatt, & Mathewes, 2013). In a water body, the deposition of pollen grains commonly relies upon two factors: its settling velocity and water movement (Brush & Brush, 1972). These factors strongly control the pollen suspension time in the water column (Brush & Brush, 1972).

Lower river discharge during the 1830–1910 drought period likely decreased pollen input from the hinterland and increased pollen deposition by reducing water flow velocity in the lagoon, hence allowing the suspended pollen grains to settle to the lagoon floor. In an estuarine environment, the pollen deposition rate is also influenced by encapsulation in floccules of clay, silt, and organic particles (e.g., amorphous OM, phytoclasts, and palynomorphs), the formation of which (=flocculation) largely depends on the salt concentration (Chmura & Eisma, 1995; Gastaldo, 2012; Gastaldo, Feng, & Staub, 1996). Higher salt content causes fine particles to stick together and to form larger and heavier aggregates, which settle more rapidly (Sutherland, Barrett, & Gingras, 2014).

In addition, lower river discharge resulted in lower sediment input into the lagoon, reducing the effect of sediment dilution (Figure 5). In an ecosystem where pollen mainly originates from local vegetation, such as in the SAL, sediment accumulation is inversely related to total pollen concentration (Brush, 1989). This means that pollen concentration increases whenever mineral input decreases, and vice versa (Brush, 1989). Therefore, the higher proportion and concentration of mangrove and mixed forest pollen during the 1830–1910 drought period is likely influenced by changes in the pollen deposition mechanisms and the effect of sediment dilution, rather than by an expansion or reduction of the source plants.

The relatively low abundance of pollen from cultivated Poaceae and taxa associated with open vegetation during the 1830–1910 drought period appears to be contrary to the large-scale land use change, marked by a considerable expansion of agriculture in the lagoon's catchment area during this period (Lukas, 2015b, 2017). These land use changes are not reflected in the sediment record, as reduced precipitation must have limited riverine pollen transport into the lagoon.

5.1.4 | The wet "human century" 1910 AD until present

After 1910, the pollen record indicates a decline in mangrove forest and most mixed forest taxa (Figure 3). It also indicates an increase of herbaceous plants, such as wild Poaceae and Ericaceae, and of coconut trees (*Cocos*; Figure 3), which are cultivated throughout the lagoon's catchment area. These changes are confirmed by similar trends in their absolute numbers (Supplementary S4), a higher $\delta^{13}C_{org}$, indicating the addition of C4 plant-derived OM, and a lower C/N ratio, which suggests the decline of vascular plant OM input (França et al., 2013; Meyers, 1994; Figure 4).

Despite being likely exaggerated by the dilution effect resulting from higher sediment input, the decline of mangrove taxa in the pollen record is in agreement with historical records of mangrove use and land conversion. The drastic decline of *Bruguiera* in the pollen record around the turn of the 20th century is in line with a forest inventory by de Haan (1931), who found that *Bruguiera* stands were particularly exploited and degraded during this period, with only limited regrowth. While exploitation of *Rhizophora* first remained limited to 100–200 m corridors along the creek shores (de Haan, 1931), our pollen record indicates a massive decline in *Rhizophora* stands until the 1940s. In addition to the wood demand of the colonial industry, local uses of mangrove wood and the expansion of agricultural land by the growing population also contributed to the decline in mangrove cover.

The pollen record also suggests an increase of cultivated Poaceae and the exotic taxon *Pinus* after 1910 (Figure 3). The increase of cultivated Poaceae pollen likely reflects the continuous expansion of rice cultivation in the catchment area combined with enhanced fluvial pollen transport due to higher precipitation. The increase in *Pinus* pollen reflects the expansion of pine plantations in the catchment area by the Colonial Forest Service and, later, the state forestry corporation. Although teak (*T. grandis*) is also widely planted in the catchment, its pollen is not captured by the pollen record. In contrast to *Pinus* spp., *Tectona* spp. pollen are poorly preserved and have a low dispersal efficiency (Quamar & Bera, 2014).

The sediment core indicates rapidly increasing sedimentation after 1960 (Figures 2 and 5). This is roughly in line with the results of a historical cartographic and remote sensing analysis of lagoon shore line changes (Lukas, 2014a, 2017), which shows continuously increasing sedimentation between the first half of the 20th century and the 1990s, with aggradation progressing from the northern to the southern parts of the lagoon where the sediment core was taken. The causes of increasing sedimentation in the second half of the 20th century include the expansion of rainfed agriculture, erosion on contested state forest and plantation lands, erosion on roads, trails, and in expanding settlement areas, "ngaguguntur" (the digging back of hill slopes), agriculture in riparian zones, and river and floodplain modifications, including the removal of river meanders (Lukas, 2017). Meander removal and river straightening artificially shortens the water flow distance and steepens the slope (Sapkota, 2017). This increases water velocity and enhances streambank and bed erosion, thus contributing to increased sediment input into the lagoon. Furthermore, a floodway was constructed to divert the peak floods of the Citanduy into the Cibeureum River and to redirect part of the high sediment load into the northern part of the lagoon, where much of it was deposited instead of being transported to the ocean (Lukas, 2017).

5.2 | Carbon sequestration in the Segara Anakan Lagoon

5.2.1 | Variation in C_{org} content

In the SAL, the negative correlation between C_{org} percentage and the Ti/Ca ratio suggests a dilution of the deposited organic carbon with an increased input of eroded mineral material from the hinterland (Figure 6; e.g., Mohtadi et al., 2011; Steinke et al., 2014). Sediment input contributes to the preservation and burial of C_{org} (Hartnett, Keil, Hedges, & Devol, 1998; Schwarzbauer & Jovančićević, 2015). However, in areas exhibiting very high sediment accumulation rates, as in the SAL, C_{org} can be diluted by inorganic clastic material, that is, the C_{org} concentration may decrease with an increasing sediment supply (Tyson, 2001). Such "dilution" only reduces the C_{org} concentration in the sediment, but not its total amount (Schwarzbauer & Jovančićević, 2015). Thus, a lower sediment input would reduce the dilution effect and result in a higher C_{org} concentration as observed in the SAL during the 1830–1910 drought period (Figure 5).

On the other hand, despite the overall rainfall control, the positive correlation between C_{org} percentage and the taxa representing mangrove forest, mangrove associates, and mixed forest reveals the significance of both hinterland vegetation and mangrove forest fringing the lagoon to C accumulation in the SAL. However, it needs to be noted that this correlation can to some extent be influenced by changes in pollen taphonomy and the effect of sediment dilution during the drought period (see Section 5.1). Nevertheless, the $\delta^{13}C_{org}$ indicates that mangrove taxa and its associates contribute significantly to the sedimentary C_{org} in the SAL throughout the whole record (Figure 4; Ometto et al., 2006; Rodelli et al., 1984).

Changes in salinity may also play an important role in determining C_{org} variations in the SAL, as indicated by the strong positive correlation between C_{org} and Cl. Salinity-induced flocculation was suggested to be an important mechanism in soil C accumulation in mangrove ecosystems by a recent experimental study (Kida et al., 2017). It was observed that humic substances exist in floccules that were formed due to the supply of sea water into the ecosystem. Organic particles, such as silt and clay, possess a negative charge and consequently repel each other, which prevents them from aggregating (Roberts, Jackson, & Smith, 2006). In the SAL, increased lagoon salinity likely adds to the cationic charge that limits or eliminates the repulsion effect which allows for an increased flocculation of organic particles (Shamlou, 1993; Somasundaran, 2006). Salinity-induced flocculation thus likely played a role in increasing the C_{org} content in the SAL during the 1830–1910 drought period (Figure 5).

5.2.2 | Significance of long-term carbon sequestration rates in the Segara Anakan lagoon

Estimating the ecosystem's C accumulation capacity by measuring short-term C sequestration using the surface sediment (≤10 years; ±5 cm depth) would only lead to an overestimation (Breithaupt, Smoak, Smith, & Sanders, 2014; Donato et al., 2011). This is primarily due to the fact that surface sediment is vulnerable to remineralization and erosion (Breithaupt et al., 2014). On the other hand, using longer term CAR measurements, for example, over a 50 to 100 year time span, would suppress the temporal scale bias and reduce the spatial variability (Breithaupt et al., 2014). Also, a 100 year time span is considered to "provide the most conservative forecast of the regional long-term rates" of C sequestration in coastal wetlands (Breithaupt et al., 2014).

In the SAL, the CAR increased over time, with the average values for the 10 and 20 year periods being almost twice as high as for the 100 year period. This is likely due to the increase in the SAL's sedimentation rate resulting from the profound land use changes in the catchment area over the past decades (Figure 5; Section 5.1). Regardless, its 100 year average CAR is similar to its average CAR for the entire measurement period (400 years; Figure 7). This suggests that a 100 year timeframe is appropriate to represent the CAR, particularly of lagoon ecosystems, on a longer time scale. Here, the 100-year CAR sequence is used to assess the SAL's C sequestration capacity in the larger scale context of mangrove-dominated ecosystems (Figure 8; Table 4).

Compared to other mangrove-fringed lagoons, such as the Celestun, Chelem, and Términos lagoons on the Yucatan Peninsula in Mexico, the SAL accumulated two to three times more carbon during the last century (Figure 8). Owing to their karstic geological conditions, lagoons on the Yucatan Peninsula receive little sediment through surface runoff or river input (Gonneea, Paytan, & Herrera-Silveira, 2004). Thus, sedimentation rates and CAR are fairly low. The Soledad Lagoon in Colombia, on the other hand, accumulated over two times more carbon than the SAL during the last century (Figure 8). Based on its geomorphology, the Soledad Lagoon can be defined as a choked lagoon (Kjerfve, 1994), as it only occasionally receives river water input (Ruiz-Fernández, Marrugo-Negrete, Paternina-Uribe, & Pérez-Bernal, 2011). Thus, it likely has a long water residence time and restricted tidal or river energy influence. This can result in rapid biomass accumulation as well as limited sediment resuspension and C export through tidal or river flushing (Kennish & Paerl, 2010).

The CAR of the SAL during the last century is in the same range as in Hinchinbrook Channel and Missionary Bay, Australia, which are also semienclosed coastal waterbodies fringed by mangroves somewhat similar to the Segara Anakan Lagoon (Figure 8). As in the SAL, these waterbodies also receive high runoff and allochthonous sediment input from rivers. However, their geomorphological settings tend to be more exposed and less protected than lagoons, which render them more prone to sediment redeposition due to wind/tidal energy and/or carbon export through tidal flushing (Brunskill, Zagorskis, & Pfitzner, 2002).

Meanwhile, the CAR of the SAL is in the same range as what is typically observed in mangrove forests, although much lower than some forest areas with unusually high CARs (Figure 8). While the CAR of mangrove core E40 located in the eastern part of the SA lagoon, which has little freshwater and allochthonous input from the hinterland, is similar to that of our core SA-2-102 obtained in the central part of the lagoon, the CAR of the latter is much lower than that of nearby mangrove core C24, whose CAR is moderately high compared to the global average (see Figure 8; Table 4; Kusumaningtyas et al., 2019). Considering that the sediment accumulation rate in the SAL has been increasing since the 1960s, and that the CAR of core C24 represents mainly that period, a comparison of the CAR in our core during the past two decades (Figure 7) with that of C24 shows that the difference is not that large. This finding, along with the high proportion of mangrove pollen and the low $\delta^{13}C_{org}$ of our core SA-2-102, indicates that a large proportion of the carbon exported from the mangrove forest is

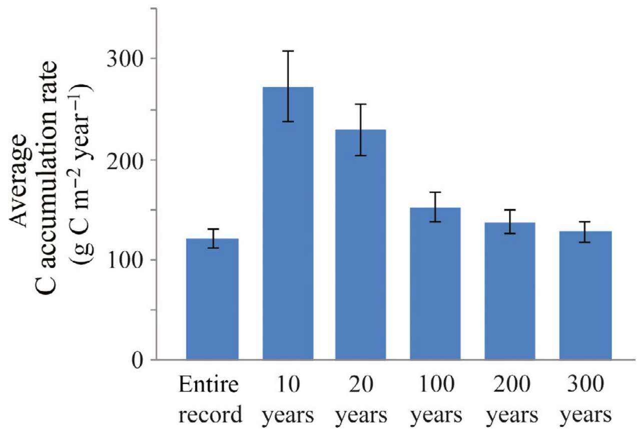

FIGURE 7 Average C accumulation rate for the SAL in different time slices

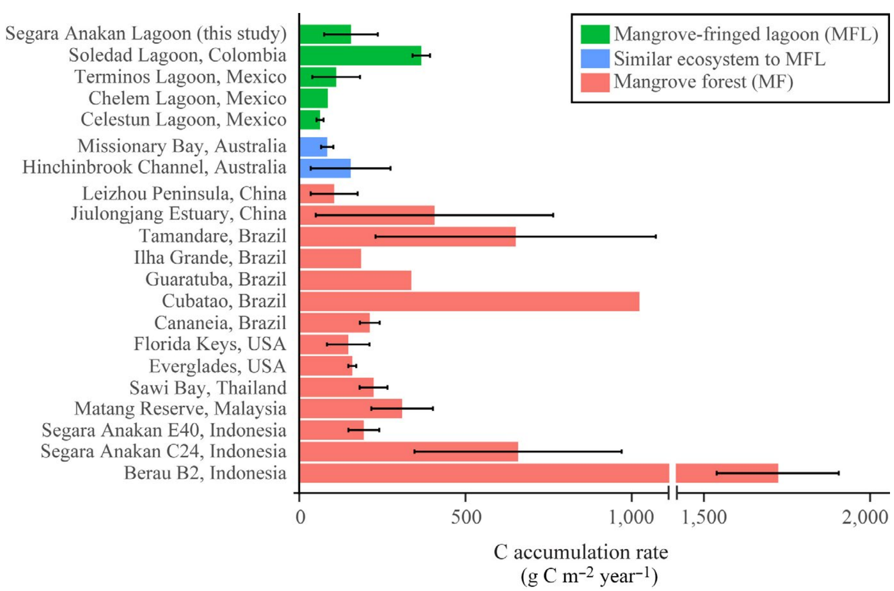

FIGURE 8 Comparison of C accumulation rates of mangrove-fringed lagoons and similar ecosystems and of mangrove forests. Extended information regarding the datasets included in the analysis is provided in Table 4

TABLE 4 Datasets included in the comparison (Figure 8)

No.	Sites			CAR (g C m^{-2} year^{-1})	Record length (years)	Data source
1	USA	Mangrove-forest (MF)	Florida Keys	147.2	<90	Callaway, DeLaune, and Patrick (1997)
2			Everglades	159.5	80–90	Smoak, Breithaupt, Smith, and Sanders (2013)
3	China		Leizhou Peninsula	105	40–60	Yang, Gao, Liu, and Zhang (2014)
4			Jiulongjang Estuary	406.7	<100	Alongi et al. (2005)
5	Brazil		Ilha Grande	186	c. 100	Sanders, Smoak, Sathy, and Patchineelam (2008)
6			Tamandare	651	60–100	Sanders, Smoak, Sathy, Sanders, and Patchineelam (2010)
7			Cananeia	213	60–80	Sanders, Smoak, Sathy, Araripe, et al. (2010); Sanders, Smoak, Sanders, Sathy Naidu, and Patchineelam (2010)
8			Cubatao	1,023	60–80	Sanders, Smoak, Sathy, Araripe, et al. (2010); Sanders, Smoak, Sanders, et al. (2010); Sanders et al. (2014)
9			Guaratuba	337	c. 70	Sanders, Smoak, Sanders, et al. (2010)
10	Thailand		Sawi Bay	223.5	<80	Alongi et al. (2001)
11	Malaysia		Matang Reserve	309.3	c. 80	Alongi et al. (2004)
12	Indonesia		Segara Anakan E40	194.1	<60	Kusumaningtyas et al. (2019)
13			Segara Anakan C24	658.2	<70	
14			Berau B2	1,722.2	<50	
15		Mangrove-fringed lagoons (MFL)	Segara Anakan Lagoon	153	c. 100	This study
16	Mexico		Celestun Lagoon	62.5	100–160	Gonneea et al. (2004)
17			Chelem Lagoon	85.5	100–160	
18			Terminos Lagoon	111	100–160	Lynch et al. (1989); Gonneea et al. (2004)
19	Colombia		Soledad lagoon	367	c. 100	Ruiz-Fernández et al. (2011)
20	Australia	MFL-like ecosystems	Missionary Bay	84	c. 100	Brunskill et al. (2002)
21			Hinchinbrook Channel	154.4	c. 100	

deposited in its vicinity. Similarly, a large amount of mangrove-derived carbon was found in the coastal sediments of Hinchinbrook Channel and Missionary Bay (Brunskill et al., 2002; Torgersen & Chivas, 1985). It is inferred that semienclosed coastal waterbodies harboring mangrove forests can be quantitatively significant repositories of mangrove carbon, which is as yet hardly considered in calculations of “blue carbon” storage in vegetated coastal habitats.

6 | CONCLUSIONS

Our study shows that environmental dynamics and carbon accumulation in the Segara Anakan Lagoon over the past 400 years were controlled by a complex interplay of climate and land use change in the lagoon and its hinterland. Four phases have been identified, during which autochthonous mangrove carbon always was a significant contributor to carbon accumulation in SAL sediments, but with varying admixtures of terrestrial carbon from the hinterland: First from natural mixed forest, and later with increasing contributions from agriculture soils (Figure 9).

Human activities have become a major driver of ecosystem dynamics in the SAL by modifying the landscape in the catchment area and the lagoon itself, similar to other coastal areas around the world (Crossland, Kremer, Lindeboom, Marshall Crossland, & Tissier, 2005). Yet reduced rainfall during dry periods moderated the impacts of anthropogenic landscape transformations in the catchment area on the SAL by reducing riverine fluxes of terrestrial material. Our study shows that in coastal ecosystems strongly connected to their watershed like the SAL, the change in precipitation (climate) is an overarching control of the "delivery of effects" of anthropogenic activities in the catchment area to the coastal ecosystem.

During the 1830–1910 drought period, our record shows a decline in rice pollen accompanied by an increase in mangrove pollen. Without knowledge of rainfall variations and anthropogenic landscape modifications in the lagoon and its catchment, this finding could easily be interpreted as indicating an expansion of mangroves

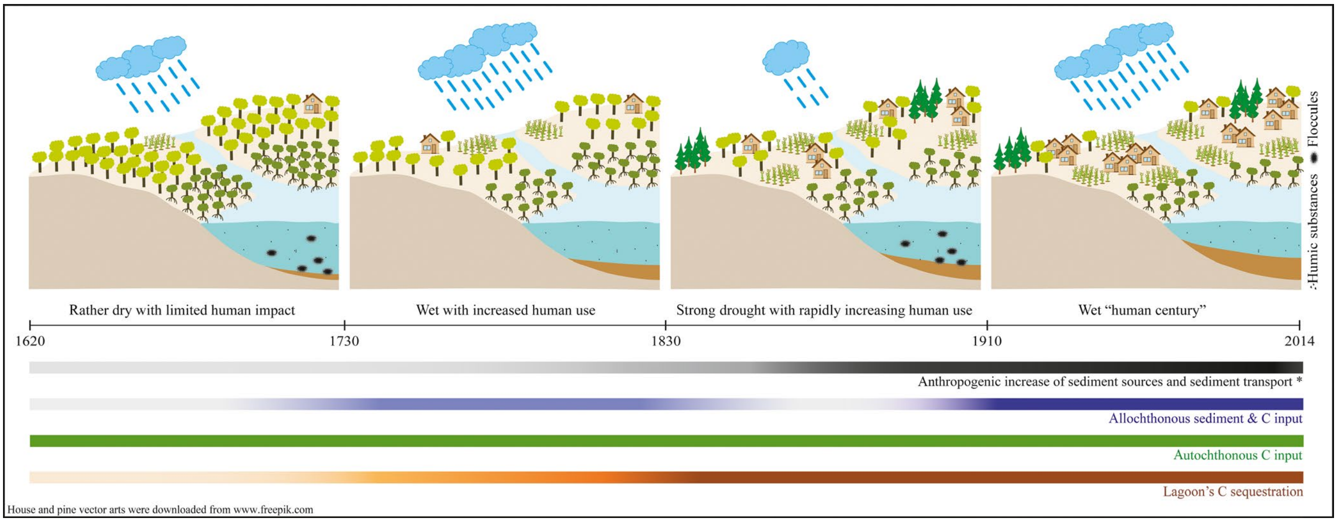

FIGURE 9 Four phases of environmental development of the SAL as controlled by the intertwined effects of climate and land use change. The division of the phases is based on the changes in precipitation in the Segara Anakan and its catchment area as indicated by Ti/Ca. (*more detailed information on the sediment sources is in Lukas, 2017)

and a decrease in agriculture. However, this period was in fact marked by a considerable expansion of agricultural areas at the expense of forested land in the lagoon's catchment (Lukas, 2017) and by increasing mangrove deforestation and degradation. However, reduced precipitation limited the riverine transport of the rice pollen to the lagoon and, by reducing freshwater input, increased the concentration of mangrove pollen. The caveats of interpreting historical records without the larger scale climactic and ecological context described above illustrates the importance of interdisciplinary research that integrates information concerning ecological and societal changes with terrestrial and coastal dynamics.

On a global scale, the Segara Anakan Lagoon is among the most effective mangrove-dominated ecosystems in terms of C sequestration (Figure 8). This results from a unique combination of high mangrove carbon input, a higher preservation rate, and contributions of allochthonous carbon due to increased sediment input from an anthropogenically modified hinterland. In light of a predicted decrease of precipitation over Java in the 21st century (Collins et al., 2013; Qalbi, Faqih, & Hidayat, 2017), it is conceivable that the existence of the mangrove forest gains importance for the carbon sink function of the SAL. Thus, restoration and sustainable management of mangrove-fringed coastal lagoons is vitally important for global climate change mitigation.

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AUTHOR CONTRIBUTION

KAH led the manuscript writing. KAH and TCJ conceived the ideas and interpreted the data. KAH and MCL analyzed the data. KAH, MCL, VK, and HB collected the data. All authors critically contributed to the manuscript draft and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The data used in the analyses are available at PANGAEA. https://doi.pangaea.de/10.1594/PANGAEA.908777

ORCID

K. Anggi Hapsari https://orcid.org/0000-0001-8328-4771
Tim C. Jennerjahn https://orcid.org/0000-0003-1022-5126
Martin C. Lukas https://orcid.org/0000-0001-8718-6300
Volker Karius https://orcid.org/0000-0002-6396-0792
Hermann Behling https://orcid.org/0000-0002-5843-8342

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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