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A mid-Holocene pollen record of mangrove diversity on the coast of Ujung Genteng, the southern edge of Sunda Shelf, Indonesia

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Abstract. *Nugroho SH, Rizal Y, Zaim Y, Yulianto E, Putra PS, Riyanto AM, Amar. 2024. A mid-Holocene pollen record of mangrove diversity on the coast of Ujung Genteng, the southern edge of Sunda Shelf, Indonesia. Biodiversitas 25: 3653-3664.* The Sunda Shelf provides the most informative data for studying mangrove ecosystems. However, the southern edge of the Sunda Shelf adjacent to the Sunda megathrust zone has yet to be studied. This study aimed to provide a paleoecology record of the Ujung Genteng mangrove ecosystem during the mid-Holocene (over 6,300 cal year BP (Before Present). We looked at changes in a mangrove ecosystem using pollen and radiocarbon data from the UG 7B core. *Rhizophora* sp. initially dominated at c. 6,200-6,100 cal year BP. The ecosystem gradually declined, transitioning to a back mangrove environment. A decrease in the mangrove and back mangrove pollen since 4,200 cal year BP, indicating a shift away from the mangrove forest. In contrast, higher non-mangrove pollen frequency indicates a closer distance to the lowland. By 400 cal year BP, all mangrove pollen vanished, and the environment became almost completely terrestrial. The implications of this research contribute to improved insights into mangrove resilience and resistance to environmental and anthropogenic stressors, aiding effective coastal management and adaptation strategies. Our study also highlights the unique conditions of Sunda Shelf paleoecology, contributing to a more comprehensive regional knowledge and offering an important reference for further investigations on coastal ecosystem dynamics.

Keywords: Biodiversity, coast of Ujung Genteng, mid-Holocene, pollen, *Rhizophora*, Sunda Shelf

Abbreviations: BP: Before Present, ca: circa, cal: calibrated, UG: Ujung Genteng

INTRODUCTION

Mangrove ecosystems, consisting of trees and shrubs growing in inter-tidal areas, are present worldwide, particularly along tropical and subtropical coasts (Tomlinson 2016). Indonesia has the largest mangrove area in the world, representing almost 23% of all mangroves (Agency of Survey Coordination and National Mapping 2009; Soeprobowati et al. 2022). The country's mangrove vegetation boasts the widest variety of plant species and compositions globally, with 43 species regarded as "true mangroves" (Kusmana 2014, 2018; Bunting et al. 2018, 2022; Ximenes et al. 2023). Mangrove forests play a vital socio-economic role by protecting coastlines, fisheries, and carbon sequestration (Ellison 2015). However, this ecosystem is easily influenced by changes in the surrounding environment, especially sea level and rainfall (Arifanti 2020). The development and compositions of mangrove ecosystems are based on several interrelated factors, such as temperature, soil, salinity, brackish puddles, sediment, tides, wave energy, and periodic factors (Godoy and de Lacerda 2014; Krauss et al. 2014).

The Sunda Shelf is one of the best places to study environmental and sea-level change. It is particularly interesting due to its significant impact on vegetation, fauna, climate, and environmental changes (Solihuddin 2014; Sathiamurthy and Rahman 2017). Its location far from the glaciation center and its stable tectonic setting since the Quaternary period makes it ideal for such studies (Hall 2014; Parham 2016; Hantoro 2018). Due to significant sea-level changes, research on environmental changes during the Holocene has become an attractive topic. Sea-level changes during the last glacial maximum and subsequent stabilization led to the formation of Sundaland, a vast landmass in the Sunda Shelf that connected the Greater Sunda Islands, including Java, Sumatra, and Borneo, with the Asian continent (Sathiamurthy and Rahman 2017; Shaw et al. 2023).

The Sunda Shelf makes it convenient to study the dynamics of mangrove vegetation. Some studies on response changes in diversity have been conducted in the Sunda Shelf, such as those by Hunt and Gilbertson (2014); Punwong et al. (2018); Englong et al. (2019); Setyaningsih et al. (2019); Yulianto et al. (2019a); Dai et al. (2023); Punwong et al. (2023), which focused on the western and northern parts of the Sunda Shelf. Pollen on the Sunda Shelf has been studied by several researchers, especially on the southern part of the Sunda Shelf in Bali by Fukumoto et al. (2015) and Sumba by Ardi et al. (2020). The southern part of the Sunda Shelf holds potential for research on climate and environmental changes.

This research was conducted on the southern edge of the Sunda Shelf, which has significant potential for studying climate and environmental changes. Its proximity to the equator and its role as the southern limit of the savanna corridor make it particularly sensitive to changes in climatology. There is a significant difference in rainfall between the northern and southern regions of the Sunda Shelf, as shown by a comparison of stalagmite δ18O values between the Flores region (Griffiths et al. 2009) and north Borneo (Partin et al. 2007) in the mid-Holocene. Mangrove pollen has been used as the proxy of mangrove dynamics since the mid-Holocene. The response of the mangrove ecosystem to natural and human influence can be obtained from pollen analysis and the continuous accumulation of sediments (Punwong et al. 2018; Setyaningsih et al. 2019). This study aimed to provide a paleoecology record in the mid-Holocene of ca 6,300-4,200 cal yr Before Present (BP) from mangrove ecosystems on the southern edge of the Sunda Shelf, particularly in Ujung Genteng Peninsular, Indonesia. This understanding guides the mitigation, adaptation strategy, and proper planning and management of coastal zones.

MATERIALS AND METHODS

Study area

A 550-cm long core (UG-7B) was collected using a Geoslicer in 2019 (Yulianto et al. 2019b) in a wetland area close to Ujung Genteng Peninsular, Sukabumi District, Indonesia. Ujung Genteng Peninsular is one of the southern Java coast which is situated at the southern edge of the Sunda Shelf with administrative regional boundaries as follows: the northern with Bogor District, the southern by Indian Ocean, the eastern by Cianjur District, and the western with Lebak District and Indian Ocean. The UG-7B core is at latitude 7° 19' 59.412" S and longitude 106° 24' 20.196" E (Figure 1). The core sample was put in a PVC pipe, wrapped in plastic, labeled with the core name, and stored in a cold room.

Physiographically, the research area is included in the southern mountainous zone (van Bemmelen 1949). The Ujung Genteng peninsula comprises surface deposits (alluvium), such as clay, silt, gravel, and coral reef limestone. Due to erosion in the upper land, the sedimentation process occurs around the mouths of large rivers such as Cimandiri, a large sedimentation process occurs during the rainy season. The southern part of West Java is tectonically close to the subduction zone in southern Java. This subduction zone stretches from western Sumatra, southern Java to Nusa Tenggara. This subduction activity is still high, which is suspected by frequent earthquakes. These parts are prone to earthquakes, which can be followed by a tsunami threat at any time. Additionally, the geological structure also controls morphological forms (van Bemmelen 1949; Wahyudin 2011).

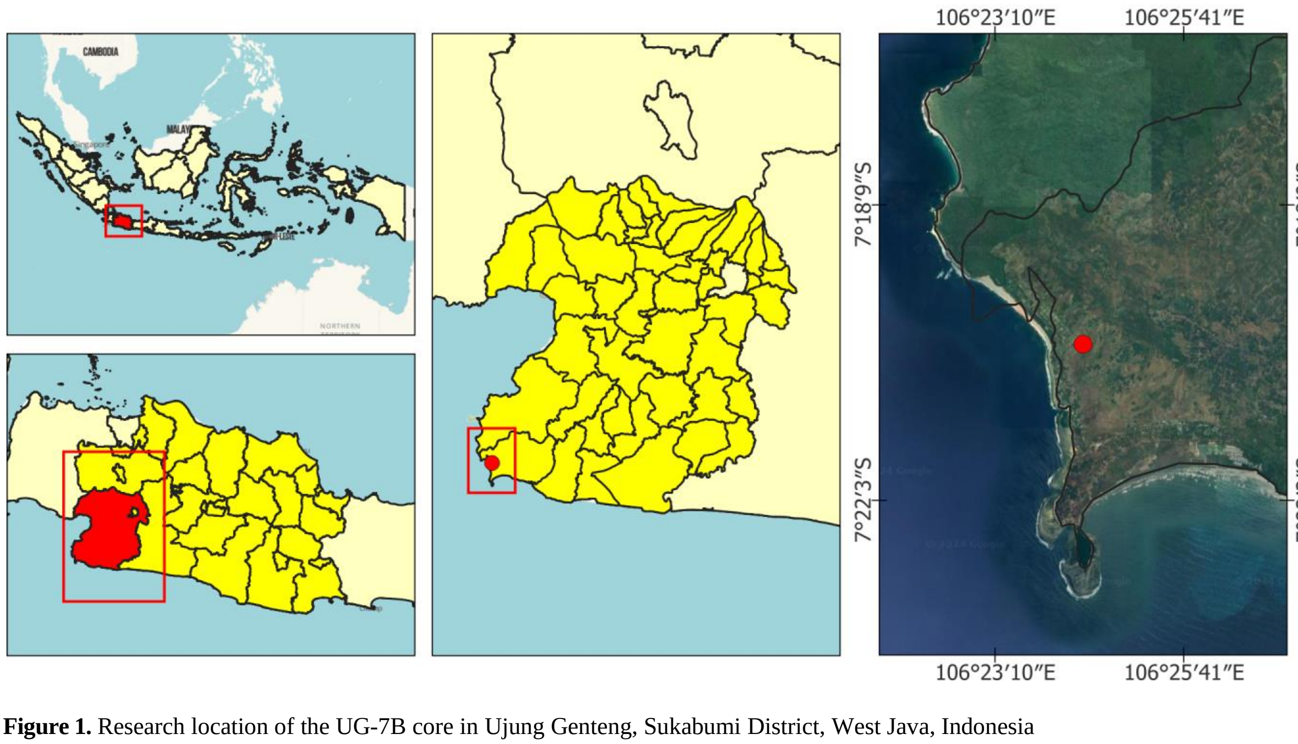

Figure 1. Research location of the UG-7B core in Ujung Genteng, Sukabumi District, West Java, Indonesia

The east monsoon, which blows from west to east from June to September, and the west monsoon, from east to west from December to March, impact the tropical climate conditions of Sukabumi District's coastal areas (Eveson et al. 2015). In the Ujung Genteng and the adjacent areas, there are 110 and 170 wet days per year in addition to 2,500 to 3,500 mm of annual rainfall (Meteorological Climatological and Geophysical Agency 2023). According to Chang et al. (2004), El Nino-Southern Oscillation (ENSO) occurrences significantly impact southern Indonesia's rainfall patterns and sea surface temperature patterns; El Nino events are frequently linked to drought years (Boer and Subbiah 2005). Furthermore, we found that rainfall during the rainy season is more sensitive. Haylock and McBride (2001) also noted that rainfall in the rainy season is more sensitive to ENSO events. Their research also found that significant El Nino occurrences, similar to or even stronger than those of 1982/83 and 1997/1998, have occurred in the past. These historical examples, such as the natural archives of Java, including tree rings, provide fascinating insights into the impact of these events on rainfall patterns (D'Arrigo et al. 2006), coral fossils (Charles et al. 2003), and lake sediments (Rodysill et al. 2012), have revealed evidence of the severe dry season that occurred at the end of the 18th century.

Some species were found in Ujung Genteng coastal vegetation, such as *Pandanus* sp., *Bambusa* sp., *Sterculia foetida* L., and *Terminalia catappa* L. This vegetation spread from Pangumbahan Beach to the mouth of the Cibareno River. Mangrove forests are found around Pangumbahan, including *Rhizophora* sp., *Bruguiera* sp., *Sonneratia alba* Sm., *Avicennia* sp., *Calophyllum inophyllum* L., *Nypa fructicans* Wurmb, and *Barringtonia asiatica* (L.) Kurz.

Procedures

Three sediment bulks were carefully selected to analyze Accelerator Mass Spectrometer Carbon (AMS 14C). The samples were sent to Beta Analytic Inc., Florida, USA. Then, the samples were prepared and examined to collect remnants of organic materials (e.g., plants and carbons). The High Probability (HPD) approach calibrated the radiocarbon dating (van der Plicht et al. 2020). INT-Cal 13 calibration datasets were employed to produce calibrated radiocarbon dating of all samples (Reimer et al. 2020). The dating model used the R-Bacon package Ver. 2.4.2 using the R-program (R Core Team 2016; Blaauw et al. 2021). A Bayesian-based statistical approach was applied using interpolation between samples subjected to carbon dating calibration, then, the sediment dating was interpreted (Blaauw et al. 2021).

Pollen analysis was conducted in a sedimentology laboratory, the Research Center for Geological Disaster, National Research and Innovation Agency (BRIN), Bandung, Indonesia. A 550-cm long sediment core was sliced to 1-cm thickness with a 10-cm interval to obtain the highest resolution, namely 100 years (centennial). This is based on research by Neuzil (1997), which states that peat has a sedimentation rate of around 1 cm/year under normal conditions. However, the study area has a sedimentation rate of around 1 cm per 4.5 years. Therefore, this study uses a sampling interval of 10 cm to describe changes in environmental conditions per 45 years. A total of 55 samples were utilized in this study.

Pollens were extracted from the sediment core using the acetolysis method (Riding 2021; Yao et al. 2023). Therefore, each sample was immersed in a 10% KOH solution to remove the hummus. Following neutralization, the samples were immersed in 40% HF, HCl 38%, $ZnCl_2$, and acetolysis solutions (a combination of Acetic Anhydride $C_4H_6O_3$ and thick sulfuric acid H_2SO_4 with a ratio of 9:1) to remove the silica, carbonate, heavy minerals, protoplasm, and other cellulose matters. Glycerine solution was incorporated into the residue that would be processed under microscopic observation and further storage (Quamar et al. 2021).

Taxonomy identification was carried out with the use of online databases for Atlas Pollen and Spore Australasia from Australia National University, Canberra (available at http://apsa.anu.edu.au), picture databases from the University of Goettingen (available at http://gdvh.uni-goettingen.de/), and mangrove pollen collections from the Department of Palynology and Climate Dynamics, University of Goettingen (Jones and Pearce 2015; Poliakova and Behling 2016; Phuphumirat et al. 2016). At least 300 pollen grains were counted from each sample. Pollen frequency was counted by removing species with the highest frequency (majority) so that the frequency patterns of minority species could be read in detail. The major species were counted separately by dividing them by the total pollen. Then, data of these pollens were presented in a pollen percentage diagram using TILIA software (Grimm 2004).

Data analysis

The use of the AMS C14 technique to plant material derived from bulk sediments improves dating accuracy. When assessing calibrated AMS 14C radiocarbon data, the calibration curve must be acceptable for both the geographical location and the time period of the sample (Reimer et al. 2020; van der Plicht et al. 2020). Advanced statistical approaches, such as Bayesian analysis, are used to provide a more robust study (Blaauw et al. 2021). After obtaining the calibration age, age modeling is used to establish the age of the stratigraphic layers and the sedimentation rate at the site. This knowledge is very valuable in comprehending the dynamics of the historical environment. This approach enables the integration of radiocarbon data with additional contextual information, such as stratigraphic sequence, global or regional event linkages, or other relevant evidence. The outcome is an adjusted age probability distribution, which gives a more realistic depiction of a sample's chronological placement (Taylor and Bar-Yosef 2014).

The identified pollen taxa were classified into mangrove and back mangrove habitats (Haseldonckx 1974), while the remaining unidentified pollen taxa were grouped into non-mangrove pollen. Mangrove pollen and back mangrove pollen, two distinct pollen grains, are invaluable tools in understanding coastal environments and, importantly, deciphering sea-level changes in geological history (Hijma et al. 2015). These pollen grains, originating from mangrove plants, are characteristic of tropical and subtropical coastal areas. Mangrove pollen is produced by true mangrove species, which thrive in the intertidal zone, enduring daily tidal water inundation and salinity conditions (Hogarth 2015). These mangrove species, including *Rhizophora* sp., *Avicennia* sp., and *S. alba*, have evolved special traits such as aerial roots and salt tolerance mechanisms to survive these harsh coastal conditions (Friess et al. 2019). In contrast, back mangrove pollen is produced by plant species that inhabit areas behind the true mangrove zone, typically in slightly higher and less saline environments (Woodroffe et al. 2016). These back mangrove species, such as *Acrostichum* sp., *Ficus* sp., and *Calophyllum* sp., are not as well adapted to the extreme conditions of intertidal zones but still reside near mangrove habitats (Hogarth 2015).

The distinction between mangrove and back mangrove pollen provides valuable insights into coastal environments and sea level changes (Woodroffe et al. 2016). However, determining forest composition is reflected in the composition of the pollen collection, not based on the characteristics of each pollen. However, other factors will determine changes in pollen composition. Mangrove pollen typically indicates shallow coastal environments, as true mangrove species require regular tidal inundation and saline conditions (Ellison and Zouh 2012). In contrast, back mangrove pollen may suggest slightly higher elevations and less saline conditions, indicative of areas further inland from the coastline (Horton et al. 2017). By analyzing the relative abundances and distributions of mangrove pollen and back mangrove pollen in sedimentary records, paleoecologists and paleoclimatologists can reconstruct past coastal environments, identify sea level changes, and understand the dynamics of coastal ecosystems over geological timescales (Hijma et al. 2015).

Non-mangrove pollen in coastal sediment records typically includes various plant types from surrounding terrestrial ecosystems. These can be broadly categorized into lowland, montane, and grassland vegetation types (Punwong et al. 2018). Lowland pollen often represents plants from tropical rainforests or deciduous forests near sea level, including various tree species and understory plants. Montane pollen originates from higher-elevation forests, including coniferous trees and other plants adapted to cooler temperatures and different soil conditions. Grassland pollen comes from open areas dominated by grasses, herbs, and shrubs, which could be natural savannas or areas modified by human activities, such as agriculture or grazing. The presence and proportions of these non-mangrove pollen types in sediment cores can provide valuable information about regional vegetation changes, climate fluctuations, and human impacts on the landscape over time.

RESULTS AND DISCUSSION

Chronology

Three radiocarbon dates were obtained from the UG-7B core sites (Table 1; Figure 2) that recorded sediments accumulated in the past 6,300 years. Careful and precise selections of radiocarbon dating allowed the samples to be utilized and observed for a coherent relationship between depth and age. The selected samples were bulk sediments extracted to obtain plant materials for further analysis. Radiocarbon analysis of the plant material was feasible to determine the age of the materials because Carbon-14 content had been decomposed since the plant died. Ideally, the sample spot selections for carbon dating were made to as many spots as possible to get the least biased dating order. Unfortunately, the organic material cannot be found in the minimum required for C-14 AMS dating in the depth interval of 0-350 cm. In this interval, the sediment is fine-grained (very fine to coarse silt). However, due to some limitations, this study selected organic material deposited in the interval depth from 350 to 525 cm in coarser silt. They represented the top depth (370 cm), middle depth (415 cm), and bottom depth (524 cm); therefore, assuming no occurrence of disorder, the sedimentation was considered constant.

The radiocarbon dating results for samples from the UG-7B core and their calibration is crucial for establishing the chronology of the core and form the basis for the age-depth model discussed earlier (Table 1). Samples were collected at depths of 370, 415, and 524 cm. The samples collected were of bulk sediment. The sample was then generated from plant material and dated using the AMS C14 technique by Beta Analytic Laboratory. Uncalibrated radiocarbon ages are commonly reported as years before present (BP, where "present" is defined as 1950 CE), with corresponding uncertainty margins. The radiocarbon dates were converted to calendar years using the IntCal-13 calibration curve (Reimer et al. 2020). These are most likely presented as age ranges with corresponding probability. Using the IntCal-13 calibration curve (Reimer et al. 2020) and the R-Bacon package (Blaauw et al. 2021; R Core Team 2016) indicates that the study uses up-to-date radiocarbon calibration methods and age-depth modeling. This adds credibility to the chronological framework of the study.

Table 1. Radiocarbons dating from UG-7B core and the calibrated dating with IntCal-13 (Reimer et al. 2020) using the R-Bacon package v. 2.4.2 (R core Team 2016; Blaauw et al. 2021)

Lab. number	Sample code	Depth (cm)	Submitter material	Analyzed material	^{14}C age (BP)	Cal ^{14}C age (BP)
Beta-516607	UG 7B A	370	Bulk sediment	Plant material	5210 ± 30	5933
Beta-631485	UG 7B B	415	Bulk sediment	Plant material	5490 ± 30	6249
Beta-516605	UG 7B C	524	Bulk sediment	Plant material	5580 ± 30	6347

Note: 14C: Carbon 14, BP: Before Present

The sediment dating was subjected to a model using the R-Bacon Ver. 2.4.2 with the Bayesian approach. An age-depth model for the UG-7B core, produced by the R-Bacon technique (Figure 2). This model is essential in paleoenvironmental investigations since it clarifies the connection between a core's age and sediment depth. Age-depth modeling is done using a Bayesian methodology called R-Bacon. Compared to more straightforward linear models, it can yield more accurate age estimations since it considers differences in sedimentation rates over time. This age-depth model is a crucial part of the research since it provides the framework for all other analyses and interpretations of the UG-7B core data. This model used the linear interpolation of calendar dating estimation based on mean values of each depth and distribution of Gaussian standard. For the dates scales, BP is used for the unit, which, in the present geology, means since 1950 AD/Anno Domini. The dates along the depth interval 0-350 cm are estimated by interpolation, assuming that 0 cm represents modern days. The top parts of the sediment core were assumed to date -68 BP, which is equal to the collection time of UG-7B, retrieved in 2018. Furthermore, the sedimentation rate is assumed to be constant. The sedimentation rate of the UG-7B core, as determined using the R-Bacon method is presented in Figure 3. The sedimentation rate in the interval 524-415 cm is low, which is about 1 cm/yr BP, while in the interval from 415 to 370 cm, the sedimentation rate increases to 6.5 cm/yr BP.

Pollen diversity

The total number of pollens presented in each sample was more than 400 grains. The number of pollens identified as mangrove pollens was approximately 7-216 grains, while that of back mangrove was 6-142 grains, and the remainder is non-mangrove pollen (including lowland, montane, and grassland) (Figure 4). At the top UG-7B core, pollen mangroves and back mangroves were nonexistent. Pollen contained in the core of UG-7B sediment showed that each sample had diverse pollen from multiple taxa, including *Avicennia* sp, *Rhizophora* sp., *S. alba*, *Sonneratia caseolaris* (L.) Engl., *Brownlowia* sp., *Calophyllum* sp., *Casuarina* sp., *Excoecaria* sp., *Nypa fruticans* Wurmb, *Oncosperma tigillarium* (Jack) Ridl., and *Pandanus* sp. (Figures 4 and 5). These taxa were grouped into mangrove and back mangrove habitats. The other unidentified pollen taxa were grouped into non-mangrove pollens.

Based on the vertical presence and frequency of pollens, the core of UG-7B sediment was divided into 6 (six) zones (Figure 6) as follows:

UG 1 zone (525-440 cm)

The average frequency of pollens in the UG 1 zone included 48.44% mangrove pollens with a relatively high frequency of *Avicennia* sp. and *Rhizophora* sp. *Rhizophora* sp. dominated the pollen groups with a 20-25% frequency. *Avicennia* sp. was present with an average frequency of 15%, which decreased upwards. Back mangrove pollens were present at 19.56%, as indicated by *Excoecaria* sp. and *N. fruticans* pollens at a lower frequency of approximately 8%. Non-mangrove pollens were present with a relatively high frequency on average, namely 52.67%, and dominated by lowlands.

UG 2 zone (440-400 cm)

UG 2 Zone differed from UG 1 zone based on the more evident representation of mangrove elements, particularly *Rhizophora* sp. Mangrove pollens were present with a dramatic increase of average frequency to 87.5%, dominated by *Rhizophora* sp. (75%) compared to the previous zone. The presence of *S. alba* showed an increase of up to 15% from the previous zone. Back mangrove pollens decreased to 16.5%, featuring a low frequency of *Casuarina* sp. dan *N. fruticans* (10%). The average frequency of non-mangrove pollens also drastically decreased to 23.25%.

UG 3 zone (400-320 cm)

UG 3 zone was dominated by back mangrove pollens with an average frequency of 16.88%. While the average frequency of mangrove pollens declined drastically to 23.69%, *S. caseolaris* had a relatively high frequency of 10%. Back mangrove pollens were dominated by *Casuarina* sp., *Excoecaria* sp., and *N. fruticans* at a frequency of 20-25%. *Brownlowia* sp. and *C. inophyllum* were present at an increasing frequency (10%) at the end of this zone and non-mangrove pollens rose to 55.25%.

UG 4 zone (320-260 cm)

UG 4 zone differed from the UG 3 zone based on the constantly decreasing representation of back mangrove pollens. The frequency of mangrove and back mangrove pollens in the UG 4 zone decreased constantly to 15% and 18.75%, respectively. Nevertheless, *Casuarina* sp., *Excoecaria* sp., and *N. fruticans* were lower than in the UG 3 zone, as indicated by the average frequency of 15%. The frequency of non-mangrove pollens dominated and peaked in the UG 4 zone up to 86.6%.

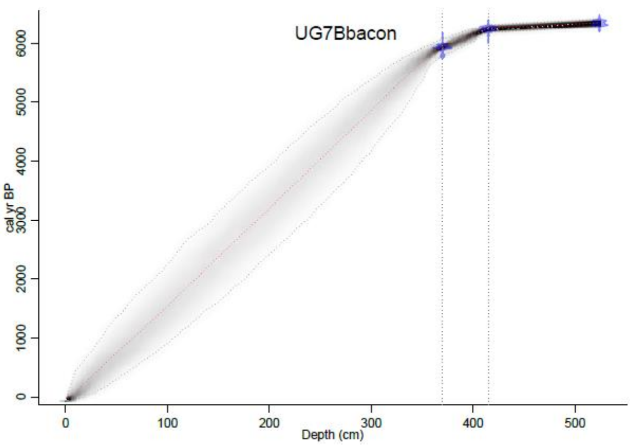

Figure 2. Age-depth modeling of the R-Bacon-generated UG-7B core. The blue symbol represents the calibrated radiocarbon-dating probability distribution function. The dotted red line indicates the mean age of each depth, the dotted line displays a 95% confidence interval, and the grey region represents the interpolated age distributions

UG 5 zone (260-30 cm)

Along the UG-7B core, the UG 5 zone had the lowest levels of mangrove and back mangrove pollens, with 3.42 and 10%, respectively, and both pollens were non-existent at the end part of the zone. The sporadic presence of *Pandanus* sp. represented the back pollen group with an average frequency of approximately 10%. Despite a decrease from the previous zone, the frequency of non-mangrove pollens was very high, up to 81.92%.

UG 6 zone (30-0 cm)

In contrast to the other zones, zone 6 had no mangrove or back mangrove pollen, which was dominated by non-mangrove pollen.

Discussion

Radiocarbon dating of core UG-7B offers a comprehensive record of the sedimentation and environmental transitions in the research region for the last 6,300 years (Figure 2). Applying AMS C14 methods to plant material obtained from bulk sediments enhances the dating precision since plant material more accurately represents the chronological order of deposition compared to bulk sediments (Taylor and Bar-Yosef 2014; Reimer et al. 2020). Analysis of the sedimentation rate reveals a very intriguing pattern (Figure 3). The comparatively modest sedimentation rate (around 1 cm/yr BP) seen in the 524-415 cm range suggests a time of relative stability or gradual deposition. Nevertheless, a notable rise in sedimentation rate (up to 6.5 cm/yr BP) within the 415-370 cm range suggests a substantial transition in environmental dynamics. This surge in sedimentation rate aligns with the mid-Holocene highstand period of the mid-Holocene, a well-documented phenomenon at many sites along the Sunda Shelf (Lovelock et al. 2015).

This was when sea levels were greater than they are now due to rising global temperatures. Rapid sea-level rise may have caused more coastal erosion and enhanced material conveyance to coastal depositional habitats. Higher sedimentation rates may suggest a time of rapid environmental transformation associated with changes in the coastline, sediment supply from land, or adjustments in coastal hydrodynamic patterns. This rapid buildup of sand may imply changes in coastal or marine processes associated with the mid-Holocene high stand.

The chronology model and sedimentation rate study of core UG-7B provide significant insights into the dynamics of coastal ecosystems along the southern periphery of the Sunda Shelf in the mid-Holocene period. Abnormalities in sedimentation rates, including a notable surge of 6,200-5,900 cal year BP, might be associated with substantial changes in the mangrove flora mix and the shoreline dynamics. These circumstances align with a highstand era during the mid-Holocene epoch, indicating a local reaction to regional trends at sea level. Although the chronological model offers a reliable period for interpretation, it is important to mention that no samples were available for dating within the 0-350 cm range because of insufficient organic material. Based on the assumption that 0 cm represents the present, the interpolation used for this period inserts a certain level of uncertainty into the chronology of the top section of the core. Although often used in paleoenvironmental research, this methodology should be used with prudence, particularly when concluding recent environmental changes (Yulianto et al. 2019a).

Diversity in pollen composition present at the sampling site was indeed seen. As expected, the relatively high numbers of certain pollen types, especially *Avicennia* sp. and *Rhizophora* sp., also correspond to a palynological-rich mangrove habitat. Perhaps most commonly, the variation in mangrove pollen can be linked to temporal and spatial dynamics within a mangrove community. This has a significant contribution overall, and back mangrove pollen is the transition zone between the two ecosystems (Tomlinson 2016). The diversity reflects the complexity of the mangrove ecosystem (Duke et al. 2007). The variety of recognized taxa signifies the power to estimate historic biodiversity for conservation and restoration actions in mangrove ecosystems within the research location (Alongi 2015). The rest were non-mangrove (lower and higher) pollen types and grasses. It would show regional connectivity, including contributions from external ecosystems (Punwong et al. 2018). The lack of mangrove pollen within the upper portion of the core, where back mangroves are also lacking, may suggest major environmental impacts such as shoreline modifications or anthropogenic disturbance (Woodroffe et al. 2016).

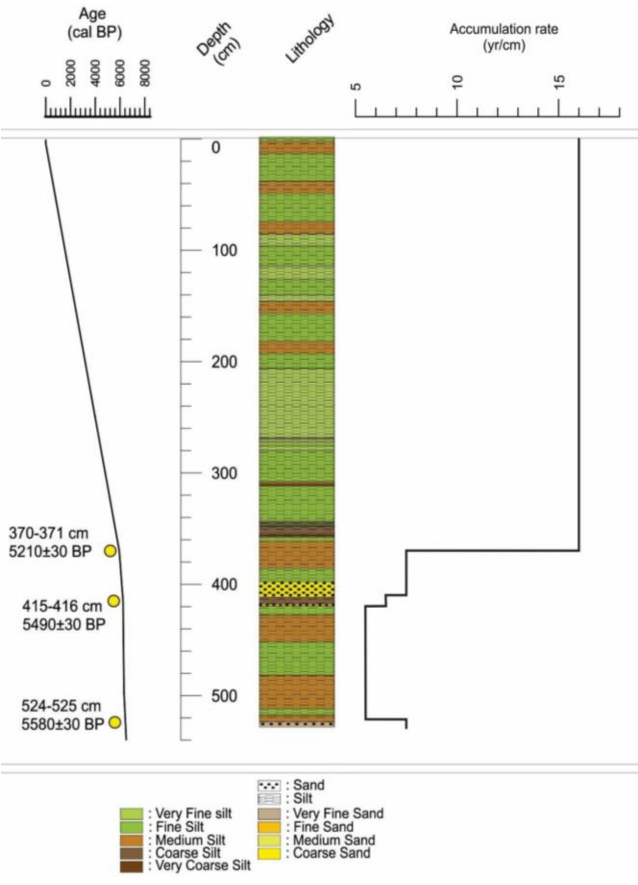

Figure 3. R-Bacon generated the sedimentation rate of the UG-7B core. The increase in sedimentation rate is related to global and regional events. In the interval 415-370 cm, the sedimentation rate increases to 6.5 cm/yr BP, which could be coeval to the mid-Holocene highstand

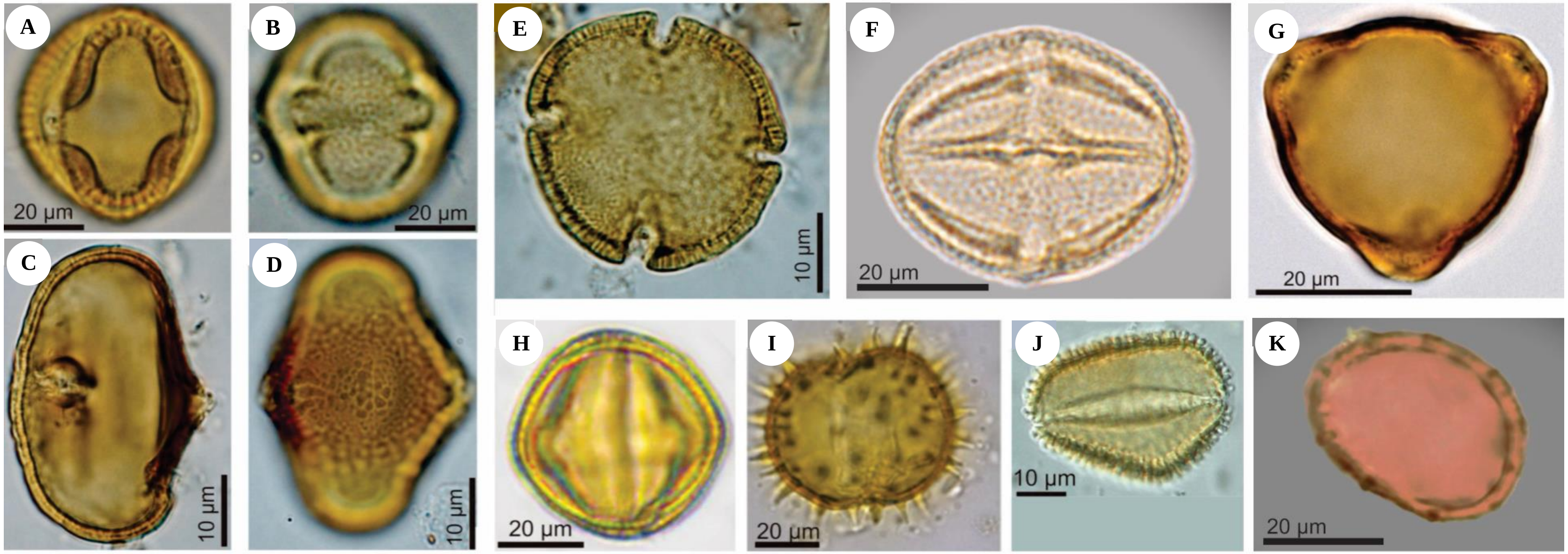

Figure 4. Main identified pollen in UG-7B. These taxa were grouped into true mangrove pollen (A-D) and back mangrove (E-K): A. *Avicennia* sp., B. *Rhizophora* sp., C. *Sonneratia alba* Sm., D. *Sonneratia caseolaris* (L.) Engl., E. *Brownlowia* sp., F. *Calophyllum inophyllum* L., G. *Casuarina* sp., H. *Excoecaria* sp., I. *Nypa fruticans* Wurmb, J. *Oncosperma tigillarium* (Jack) Ridl., K. *Pandanus* sp.

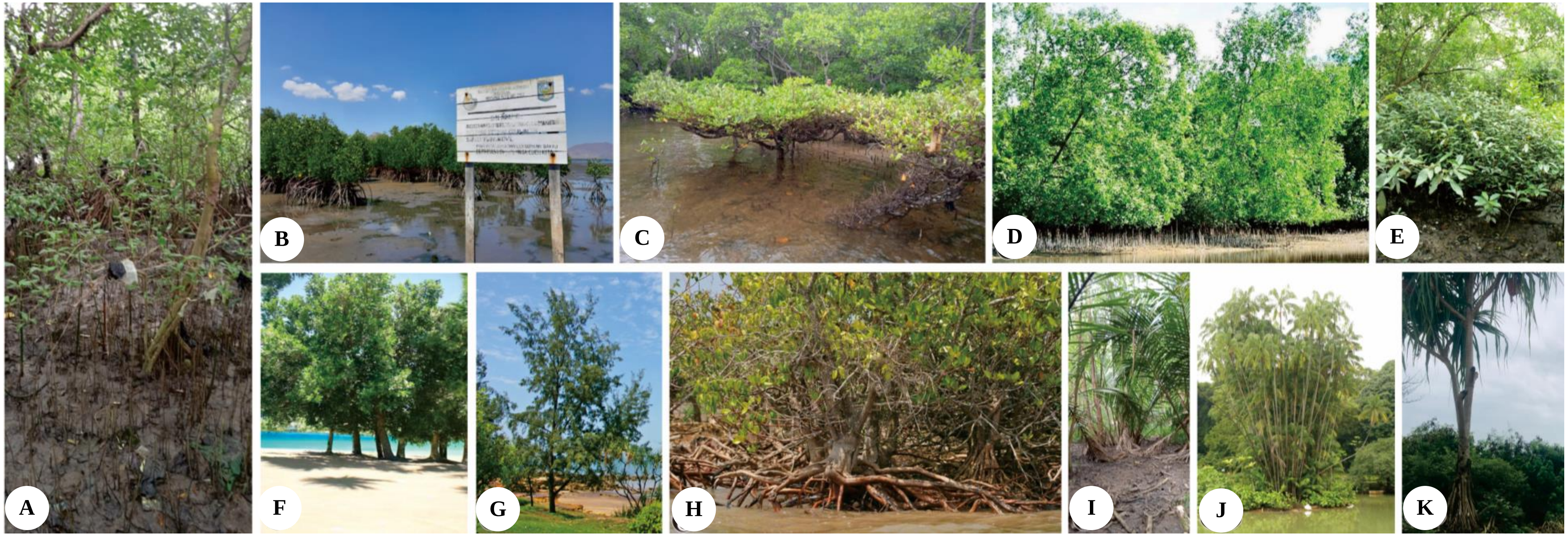

Figure 5. Examples of mangrove-forming trees: A. *Avicennia* sp., B. *Rhizophora* sp., C. *Sonneratia alba* Sm., D. *Sonneratia caseolaris* (L.) Engl., E. *Brownlowia* sp., F. *Calophyllum inophyllum* L., G. *Casuarina* sp., H. *Excoecaria* sp., I. *Nypa fruticans* Wurmb, J. *Oncosperma tigillarium* (Jack) Ridl., K. *Pandanus* sp.

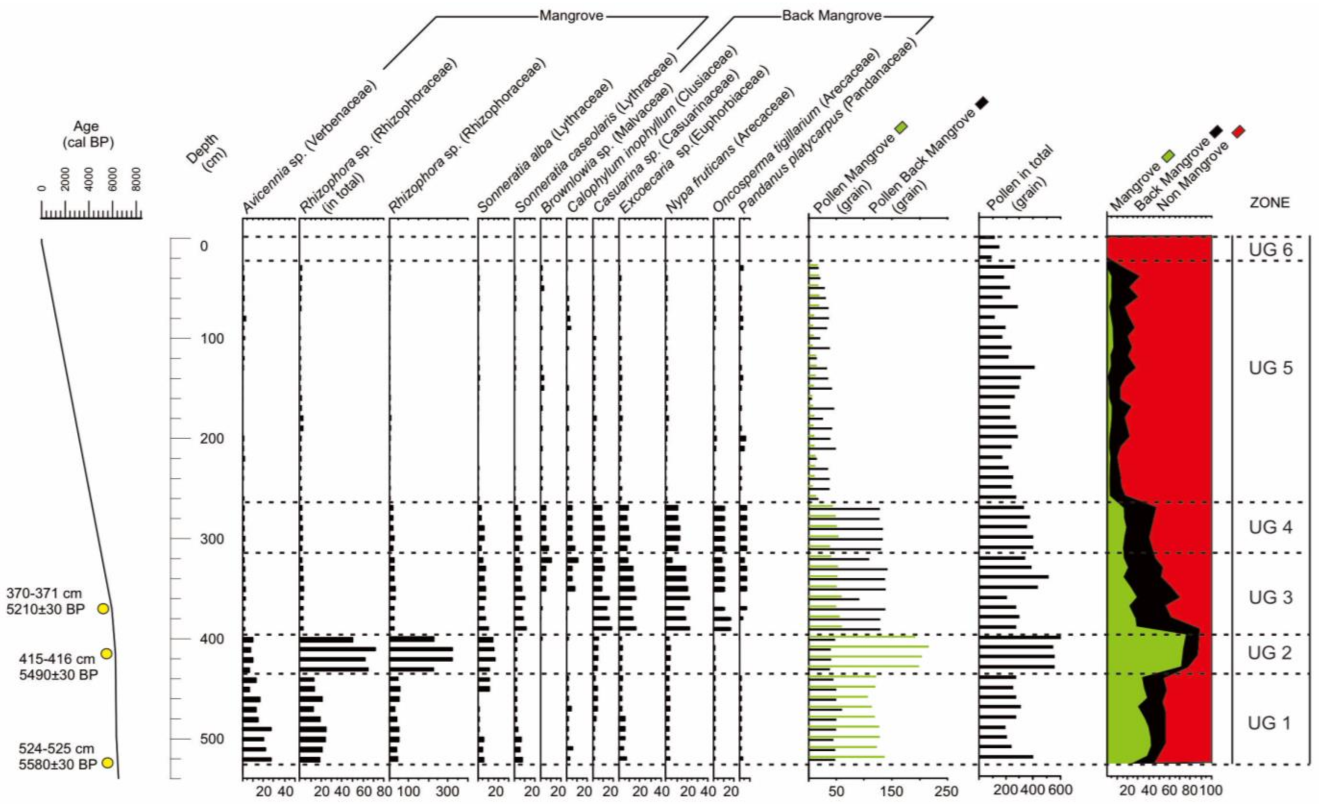

Figure 6. Pollen diagram of UG-7B core with taxa grouped into mangrove, back mangrove, and non-mangrove (consisting of lowland, montane, and grassland)

A significant representation of *Rhizophora* sp. and mangrove in the pollen groups of the core of Ujung Genteng coast has shown a strong vegetative influence on the local areas surrounding the core. The presence of non-mangrove components demonstrates that the pollens are sourced from the nearby vegetation and the one far from the highland around it. The pollen groups found in the samples showed that the frequency was insufficient to represent the ecological composition of the forests. It was probable that the pollen diagram illustrated vegetative diversity around the drill core at a certain distance but could not show a thorough reconstruction of the vegetative landscape (Figure 6). This finding followed the pollen facies mapping conducted by Xu et al. (2016) and Englong et al. (2019). The pollen diversity and frequency dynamics may have represented the changes in the closest pollen source, like mangrove forests. Therefore, mangrove forests have grown extensively in the land close to the location of the core for at least 6,300 years BP. However, its mangrove abundance may have significantly decreased since approximately 4,200 years BP.

The high frequency of mangrove dominated by *Rhizophora* sp. at the bottom core of UG-7B at 525-440 cm depth shows that the drill core is very close to the mangrove forest environment during ca 6,300-6,200 cal year BP. Non-mangrove plants, especially lowland plants, have quite a large percentage, and the rate of sedimentation that occurred during this period was quite slow. This indicates that during this period, the environmental conditions were dry, and there was a possibility of low rainfall because the sedimentation rate was lower. However, *Avicennia*'s high presence shows that the sea's influence is large because *Avicennia* sp. lives in high-salinity environments. *Rhizophora* sp. increased drastically at a depth of 440-400 cm, showing that the mangrove environment is situated at the location of drill core sediment during 6,200-6,100 cal year BP. This may be related to the mid-Holocene high stand; the high presence of *Rhizophora* sp., followed by *Avicennia* sp. (although not much), indicates that the environment is not high in salinity. It is in line with findings of surface sedimentation in the Upper Gulf of Thailand (Punwong et al. 2018), China (Xu et al. 2016), and Zanzibar (Punwong et al. 2013a, 2013b) that is indicative of mangrove pollen domination in the palynology spectrum of the surface sediment collected from around the mangrove forest. Nevertheless, both studies only present quantitative data. Punwong et al. (2013a, 2013b), Xu et al. (2016), and Phuphumirat et al. (2016) revealed that the distinctive feature of the palynology spectrum of surface sediment in mangrove forests is *Rhizophora*'s >50% frequency.

At a depth of 400-260 cm, there are changes in the composition and frequency of pollens at the UG-7B core at the age of 6,100-4,200 cal year BP. The increased compositions of back mangrove pollens indicate that the UG-7B core is sedimented in or near the back mangrove environment. At the end of this period, freshwater may have more influence than in the previous period, as indicated by the increase of *S. caseolaris*. In addition, the domination of *N. fruticans* illustrates the influence of the land environment when the stratigraphy was sedimented. *N. fruticans* needs many freshwaters to grow (Phuphumirat et al. 2016). As the frequency of mangrove and back mangrove pollens declines from the depth of 260 cm up to 30 cm (approximately from 4,200 to 400 cal year BP), it indicates that the UG-7B core has gone further from the mangrove forest. The increased frequency of non-mangrove pollens may also demonstrate the closer proximity of the UG-7B core with the lowland forest. The decline of the mangrove ecosystem in the Ujung Genteng region after 4,200 cal year BP was likely caused by a combination of environmental and human factors. Environmental factors may have included climate changes affecting temperature and rainfall patterns, sea level fluctuations, and natural coastal processes. Human activities could have involved land clearing for early agriculture or settlements, harvesting mangroves for wood, and possible alterations to coastal hydrology. However, without specific studies from this region and period, it is not easy to pinpoint the exact causes or their relative importance. A comprehensive understanding would require detailed paleoecological and archaeological research focused on the Ujung Genteng area during this time. This would help determine the precise environmental shifts and human activities that contributed to the mangrove decline in this specific location.

The top part of the core is characterized by the missing mangrove and back mangrove pollens at depth of 30-0 cm (approximately 400 cal year BP until the present day), which is generally considered as the consequence of significant activities of humans, particularly deforestation that changes mangrove for other purposes like agriculture and settlement. This result aligns with the findings of Moraes et al. (2017); van der Kaars and van den Bergh (2004), who based their research on the State of Bahia in northeastern Brazil and Banten Bay, respectively, where clear evidence of the substantial effects of intensive human activity dates back to 1,550 AD or around 400 cal BP. The disappearance of mangrove and back mangrove from the UG 7B core sediment since ca. 400 cal year BP, attributed to human activities, has significant implications for coastal management and conservation. This loss likely increased coastal vulnerability to erosion and storms, reduced biodiversity, and impacted local fisheries and carbon storage capacity. It provides important historical context for setting realistic restoration goals and understanding long-term ecosystem changes. The findings emphasize the need for stricter regulation of coastal development, integrated coastal zone management, and ongoing ecosystem monitoring. Conservation strategies should balance human needs with ecosystem preservation and restoration, including mangrove replanting efforts and sustainable resource use practices. This historical evidence underscores the importance of comprehensive, long-term coastal management approaches considering ecological and human factors.

Mangrove ecosystems are shaped by human activities, natural environmental changes, and specific ecological conditions (Punwong et al. 2018; Hapsari et al. 2018, 2022). Temperature variations, soil types, and salinity levels are crucial in determining mangrove growth, distribution, and community composition. These ecological factors work alongside broader environmental changes like sea-level fluctuations, climate variations, and human impacts to influence mangrove ecosystems over time. Understanding this multifaceted dynamic is essential for interpreting historical changes in mangrove pollen records, comprehending current ecology, and predicting future trends. This holistic approach, which considers large-scale environmental shifts and local ecological conditions, is vital for developing effective conservation and management strategies for these sensitive and important coastal ecosystems. The decline of mangrove ecosystems on the Sunda Shelf's southern edge could significantly impact coastal areas. Mangroves are natural barriers against erosion, tsunamis, and storms, provide crucial habitats for diverse species, and support important fisheries. Their loss could lead to increased coastal erosion, reduced biodiversity, and decreased fish populations. Additionally, mangroves play a role in carbon sequestration, sediment stabilization, and water filtration. Their disappearance might result in altered sediment dynamics, reduced water quality, and increased atmospheric CO_2 levels. Local communities relying on mangroves for resources could face economic challenges. Overall, the decline of mangroves could trigger cascading effects on the broader coastal ecosystem, potentially leading to significant ecological and socio-economic changes in the region.

In conclusion, radiocarbon dating of core UG-7B provides a comprehensive record of sedimentation and environmental transitions in the region over the past 6,300 cal year BP. A study of mangrove ecosystems in the Ujung Genteng area, Indonesia, revealed high frequencies of *Rhizophora* sp. in the bottom core of UG-7B, indicating proximity to mangrove forest environments during approximately 6,300-6,200 cal. B.C. Non-mangrove plants, especially lowland plants, suggest a dry environment. The decline of the mangrove ecosystem is likely due to environmental and human factors, including climate change, sea-level fluctuations, and natural coastal processes. The loss of mangroves and back mangrove pollen at depths of 30-0 cm (top of core) highlights the need for stricter regulation of coastal development, integrated coastal zone management, and ongoing ecosystem monitoring.

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