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RESEARCH ARTICLE

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Sea level rise and climate change acting as interactive stressors on development and dynamics of tropical peatlands in coastal Sumatra and South Borneo since the Last Glacial Maximum

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Abstract

Southeast Asian peatlands, along with their various important ecosystem services, are mainly distributed in the coastal areas of Sumatra and Borneo. These ecosystems are threatened by coastal development, global warming and sea level rise (SLR). Despite receiving growing attention for their biodiversity and as massive carbon stores, there is still a lack of knowledge on how they initiated and evolved over time, and how they responded to past environmental change, that is, precipitation, sea level and early anthropogenic activities. To improve our understanding thereof, we conducted multi-proxy paleoecological studies in the Kampar Peninsula and Katingan peatlands in the coastal area of Riau and Central Kalimantan, Indonesia. The results indicate that the initiation timing and environment of both peatlands are very distinct, suggesting that peat could form under various vegetation as soon as there is sufficient moisture to limit organic matter decomposition. The past dynamics of both peatlands were mainly attributable to natural drivers, while anthropogenic activities were hardly relevant. Changes in precipitation and sea level led to shifts in peat swamp forest vegetation, peat accumulation rates and fire regimes at both sites. We infer that the simultaneous occurrence of El Niño-Southern Oscillation (ENSO) events and SLR resulted in synergistic effects which led to the occurrence of severe fires in a pristine coastal peatland ecosystem; however, it did not interrupt peat accretion. In the future, SLR, combined with the projected increase in frequency and intensity of ENSO, can potentially amplify the negative effects of anthropogenic peatland fires. This prospectively stimulates massive carbon release, thus could, in turn, contribute to worsening the global climate crisis especially once an as yet unknown threshold is crossed and peat accretion is halted, that is, peatlands lose their carbon sink function. Given the current rapid SLR, coastal peatland managements should start develop fire risk reduction or mitigation strategies.

KEYWORDS

ENSO, fires, multiple stressors, paleoecology, precipitation, sea level, vegetation

1 | INTRODUCTION

Tropical peatlands in Southeast (SE) Asia have important ecosystem functions and services, for example, to store carbon (Page et al., 2010), to provide habitat for a specialized flora adapted to a nutrient-poor, acidic and waterlogged environment (Posa et al., 2011; Yule, 2010), to provide livelihood and other resources for local communities, water regulation, recreation and education (Rieley, 2007). In SE Asia, peatlands are distributed mainly in Indonesia and Malaysia (ca. 13.43 and 2.6 Mha, respectively) (Anda et al., 2021; Page et al., 2011) with a large portion being located in the coastal areas of Sumatra and Borneo (Dommain et al., 2011; Veloo et al., 2014).

SE Asian coastal peatlands (<50 km from the coastline; Dommain et al., 2014) were assumed to evolve from mangrove swamps (Anderson & Muller, 1975), and confirmed by studies from the Batanghari deposit in Jambi (Sabiham, 1988), Mendaram in Brunei (Dommain et al., 2015) and Batu Niah, Sarawak, Malaysia (Cole et al., 2015). However, some studies show that there are more variations in terms of timing, condition and driving factors, and in the development and evolution of coastal peatlands in SE Asia than previously thought (Hapsari et al., 2017; Haseldonckx, 1977; Morley, 1981; Taylor et al., 2001). Knowing how peatlands evolve over time can give valuable insights on the factors that influence peatland dynamics and functioning. Such information is valuable for developing suitable conservation, management, or adaptation action, in particular considering the ongoing and upcoming pressures on these peatlands. For example, studies in Kutai show that peat swamp forest (PSF) succeeded a shoaling *Pandanus*-dominated lake and recurrent severe fires throughout the late Holocene have caused peat truncation and lake formation there (Dommain et al., 2014; Hope et al., 2005). Peatland management can then opt to plant *Pandanus* to rehabilitate deeply flooded degraded areas where most other PSF plants cannot grow anymore (Giesen & van der Meer, 2009), and to intensify fire prevention efforts on previously burnt locations to prevent permanent peat loss.

Since the 1980s, anthropogenic impacts have been a major threat to SE Asian peatlands. Peatlands become popular for development and agricultural expansion as arable land becomes more and more rare following population growth (Schoneveld et al., 2019; Surahman et al., 2019). Between 1990 and 2015, 50% (7.8 Mha) of the peatland area in Peninsular Malaysia, Sumatra and Borneo had been converted into plantations (e.g., oil palm, pulp and rubber), agricultural land and settlements (Miettinen et al., 2016). The remaining 4.6 Mha peatlands throughout this region are still forested, but only 1 Mha is considered pristine (Miettinen et al., 2016). This not only disturbs the peatlands' ecohydrology, that is tightly linked to their C storage and sink function, but also endangers the specialized taxa living in the ecosystems (Petrenko et al., 2016; Wijedasa et al., 2017).

The threats to these ecosystems, however, are not exclusively anthropogenic, but also natural. The maximum peat growth is limited by the elevation and maximum possible height of its water table mound (Ingram, 1982). In particular for the SE Asian peatlands, it is constrained by the regional hydrological balance (Dommain et al., 2011, 2014). Peatlands are also vulnerable to climatic change for they are generally sensitive to changes in precipitation and temperature (Couwenberg et al., 2010; Page et al., 2011) and quantitative research has been developed and widely used to predict the future responses of peatland toward global change (e.g., Cobb et al., 2017; Hoyt et al., 2020; Whittle & Gallego-Sala, 2016).

Temperature increase, precipitation decrease and greater seasonality can lead to a lowered and more fluctuating peat water table, thus enhancing organic matter breakdown in tropical peatlands (Cobb et al., 2017; Warren et al., 2017). Recent climate projections for SE Asia by the IPCC suggest a temperature increase of 3–5°C and complex patterns of change in precipitation distribution even in the moderate RCP4.5/SSP2-4.5 scenarios (Ranasinghe et al., 2021; Tangang et al., 2018). An increase in mean precipitation over most parts of SE Asia is projected with medium confidence and an increase in heavy precipitation events is projected with high confidence. However, IPCC and comprehensive regional climate simulations suggest a drying tendency in Indonesia (Ranasinghe et al., 2021; Tangang et al., 2020). As much as 20–30% rainfall reduction is predicted for Sumatra and Kalimantan, where most of the SE Asian peatlands lay (IPCC, 2021; Tangang et al., 2020); thus, a negative impact of climate change on peatlands in SE Asia seems inevitable. Extreme weather phenomena, for example, El Niño-Southern Oscillation (ENSO) events became stronger and more difficult to predict in the recent past (Freund et al., 2019). Not least to mention are the threats to coastal peatlands posed by sea level rise (SLR) with a projected increase of around 1.6 m per century (Jevrejeva et al., 2010) that could lead to salinization via saltwater intrusion or inundation (Whittle & Gallego-Sala, 2016).

These threats sometimes can co-occur and/or interact with each other which can result in additive, antagonistic or synergistic effects (Burton et al., 2020). For example, strong ENSO events in 1997 and 2015 have exacerbated the severity of peat fires caused by anthropogenic activities (Fanin & van der Werf, 2017; Page et al., 2002; van der Werf et al., 2008). Advancing our understanding on the interaction and cumulative impact of multiple stressors has currently become imperative in global change biology (Orr et al., 2020). To be able to project the cumulative impact of multiple stressors, either natural and/or anthropogenic, on peatland ecosystems more accurately, the influence of each factor and their interactions need to be well understood. However, the intense anthropogenic intervention during recent decades has overshadowed or masked the influence of natural factors, making it difficult to assess the contributions of natural drivers to environmental changes separately from human activity. Thus, it is important to understand the natural drivers of peatland development during times with little or no human intervention. Such insights can be obtained using long-term ecological or paleoecological information that can extend back to several centuries or even millennia ago, prior to current human-induced intensive and rapid land use change.

To improve our understanding of the development and dynamics of coastal peatlands in SE Asia and their responses to environmental changes, we conducted multi-proxy paleoecological studies in two coastal peatlands in Riau, eastern Sumatra and Central Kalimantan, southern Borneo, Indonesia. Due to complex interactions throughout the ecosystem, the use of multiple characteristics or proxies is important to gain a wider and more comprehensive overview of the ecosystem (Birks & Birks, 2006). Here, we addressed the following specific research questions: (1) When and how did the initiation of peatlands in coastal Riau and Central Kalimantan take place? (2) How did the peatlands in coastal Riau and Central Kalimantan respond to changes in sea level and precipitation? (3) Did the peatlands in coastal Riau and Central Kalimantan experience early anthropogenic activities?

2 | METHODS

2.1 | Study sites

The Kampar Peninsula and Katingan peatlands (ca. 647,000 and 200,000 ha, respectively; Figure 1) are among the last remaining large peatlands in Indonesia (Ceruti, 2016; Katingan Project, 2014). Both sites are located in the climate region 1 that is strongly influenced by the Australian monsoon (Aldrian & Susanto, 2003). The Kampar Peninsula peatland is located on the coastal area of Riau Province, Sumatra. It is bordered by the Kampar River in the south and by the Siak River and the Selat Panjang in the north. The area experiences two dry periods per year, from January to March and from June to September with an average annual temperature and precipitation of 27°C and 2100 mm year^{-1}, respectively (Hutabarat et al., 2017). The Kampar Peninsula peatland is considered to be the largest and the thickest single peat deposit in Southeast Asia and stores at least 2.5 Gt C (Hutabarat et al., 2017). It covers ca. 344,000 ha PSF (Ceruti, 2016), with several abundant species such as *Shorea teysmanniana*, *Syzigium* sp., *Tristaniopsis* sp., *Campnosperma coriaceum*, *Austrobuxus nitidus*, *Stemonurus secundiflorus* and *Combretocarpus rotundatus* (RER-FFI, 2016).

The Katingan peatland is located in the Central Kalimantan Province, southern Borneo. It is bordered by the Mentaya (Sampit) River in the west and the Katingan River in the east, with the latter separating the peatland from the Sebangau National Park. The area experiences a wet season from November to April and a dry season from June to September, with an average annual temperature and precipitation of 27°C and 2800 mm year^{-1}, respectively (Katingan Project, 2014). The Katingan peatland stores an estimated 0.55 Gt C in peat and harbors around 140,000 ha PSF with several common species such as *Campnosperma* sp., *Callophylum* sp., *Dyospiros* sp., *Palaquium* spp., *Vatica rasak*, *Shorea balangeran* and *Dacrydium becarii* (Katingan Project, 2014).

2.2 | Peat core sampling and analyses

In November–December 2018, peat cores from the Kampar Peninsula (KP; 930 cm; 0˚23'20'' N, 102°45'34'' E) and Katingan (KTG; 910 cm; 2°51′59″S, 113°08′11″E) were retrieved using a modified Livingstone corer, 36 and 20 km from the shoreline, respectively. The surface elevation of the core sites (KP 15 m a.s.l.; KTG 27 m a.s.l.) was determined using a handheld Garmin GPSmap with 4 m vertical error under closed canopy (Wing & Eklund, 2007). The cores were extruded, split and described following the SE Asian peat classification system (Figure S1; Wüst et al., 2003). In all, 15 and 19 selected materials (macrobotanical remains and sieved (<100 μm) material) from KP and KTG cores, respectively, were sent to the Poznan Radiocarbon Laboratory, Poland, for AMS radiocarbon dating (Table S1). The dates obtained were used to construct the chronological model (Figure S2) and to calculate the peat accumulation rates (mm year^{-1}) of the KP and KTG. The age-depth models were constructed using the Bacon script (Blaauw & Christen, 2011) in R (R Core Team, 2020) and IntCal20 (Reimer et al., 2020) and SHCal20 (Hogg et al., 2020) for the KP and KTG cores, respectively. The presence of gaps and wood layers filling the whole tube core were treated as instantaneous depositional event (*slump*) in the model.

To determine the organic matter (OM) content of the peat, Loss-On-Ignition (LOI) analysis (Chambers et al., 2011) was conducted on both cores by taking 46 and 55 samples along the KP and KTG peat sections, respectively (detail sub-sample depth in Supplementary S1). The samples were then weighed, dried at 105°C for 24 h and combusted at 550°C for 4 h. To trace the source of OM, 154 and 168 samples were taken along the KP and KTG cores, respectively, for stable organic carbon isotope ($\delta^{13}C_{org}$) analysis. The samples were dried at 105°C for 24 h, finely ground, weighed (ca. 1.5 mg) and treated with 1N HCl to remove carbonates prior to the determination of organic carbon content (C_{org}) using high temperature oxidation in a Euro EA3000 elemental analyzer. Samples for $\delta^{13}C_{org}$ (‰) analysis were weighed based on the C_{org} content of each sample and treated similarly prior to the determination in a Thermo Finnigan Delta Plus gas isotope ratio mass spectrometer after high temperature combustion in a Flash 1112 EA elemental analyzer, with ±0.1‰ uncertainty of each measurement.

To reconstruct the past vegetation changes, 65 and 76 sub-samples were taken from the KP and KTG cores, respectively. The sub-samples were then processed for pollen and spore extraction following standard methods (Faegri & Iversen, 1989). Lycopodium marker tablets were added to each sample. The extracted pollen and spores were identified to the lowest possible level of taxonomic classification taxa using the reference collection of pollen and spores at the Department of Palynology and Climate Dynamics, University of Goettingen and other available literature (e.g., Anderson & Muller, 1975; Cheng et al., 2020; Hofmann et al., 2019; Jones & Pearce, 2015; Pollen and Spore Image Database of the University of Goettingen). The pollen and spores were counted to reach a minimum of 300 pollen grains for each sample, except for the three bottom-most samples from the KTG core due to very low pollen concentration. The proportion of pollen was calculated based on the total pollen counted, while the proportion of spores was calculated based on the sum of pollen and spores.

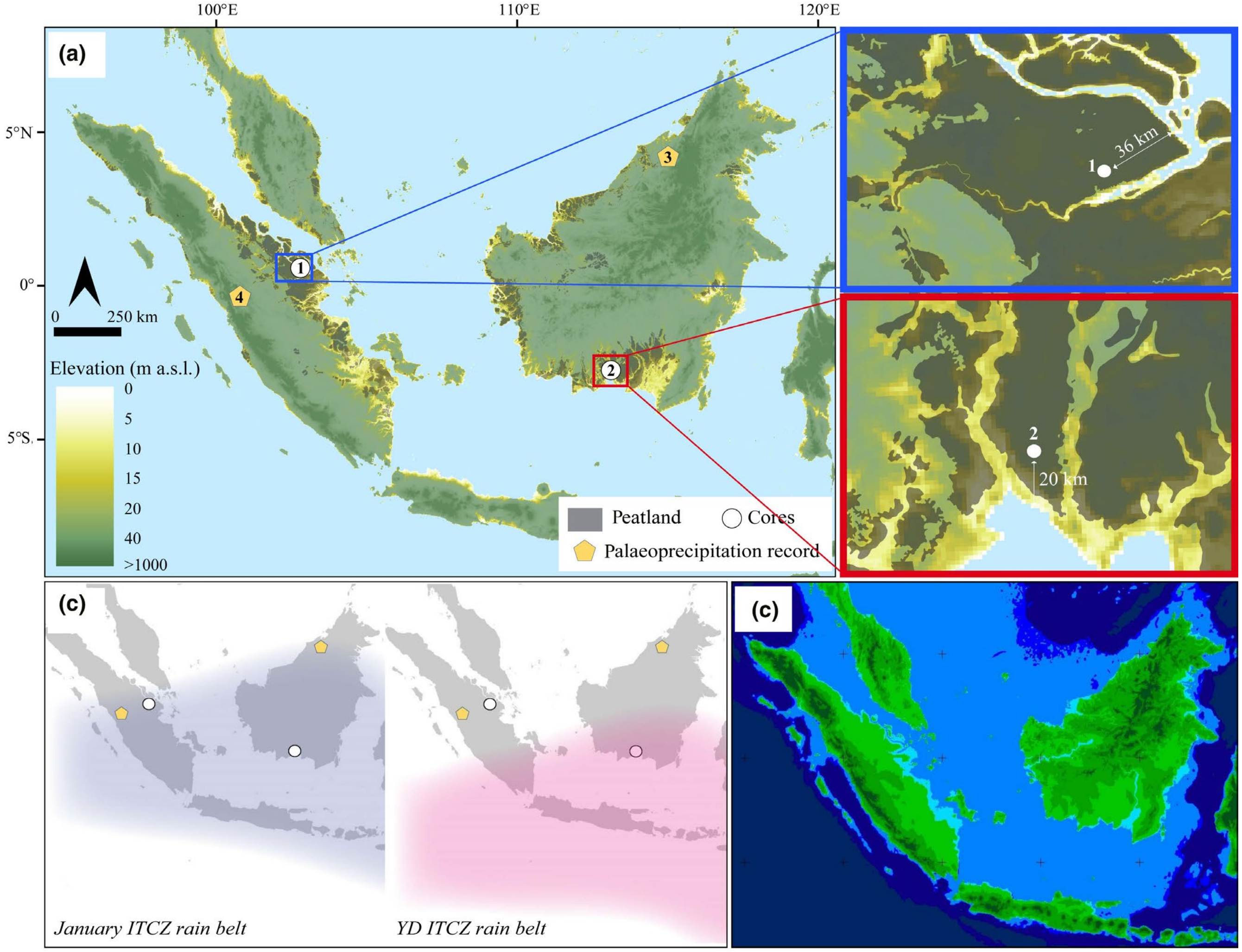

FIGURE 1 (a) Map of the study sites. The core locations are indicated by white circles: Kampar Peninsula (1) and Katingan (2) peatlands. Paleoprecipitation records are from Bukit Assam Cave, Gunung Buda, Sarawak (3; Chen et al., 2016) and Tangga Cave, West Sumatra (4; Wurtzel et al., 2018). (b) The location of the January ITCZ rain belt in present day (blue shade) and during the Younger Dryas (YD—pink shade) (after Denniston et al., 2016; Kuhnt et al., 2015). During Heinrich Stadials, the ITCZ moved not as far south as during the YD. (c) Map of Sundaland during the Holocene maximum (Sathiamurthy & Voris, 2006). The light blue color shows the submerged location of current Sumatra, Malaysia Peninsula, Borneo and Java islands when sea level was +5 m

The pollen taxa were grouped into the categories of "mixed forest" (MXF), representing pollen produced by plants growing in lowland and other types of forest; "peat swamp forest" (PSF), representing pollen of plants commonly found in peat swamp forest; "open vegetation" (OV), representing pollen produced by herbaceous plants; "riparian" (RP), representing pollen of plants commonly growing on floodplain areas or along rivers; "mangrove and mangrove associate" (MMA) which represents pollen produced by salt tolerant plants; and "long distance" (LD) represents pollen that are likely originating far from the deposition site (e.g., Cole et al., 2015; Lemmens et al., 1995; Soerianegara & Lemmens, 1993; Sosef et al., 1998).

To study the past fire regime of the peatlands, macro- and microcharcoal analyses were conducted. Microcharcoal or charcoal particles <150 µm mainly come from regional sources, that is, >20 km from the study site (Tinner & Hu, 2003), while macrocharcoal (>150 µm) typically represents the occurrence of local fire ca. 1 km from the study site (Higuera et al., 2010).

Microcharcoal was counted on the same slides for pollen and spore analysis using Clark's point count method (Clark, 1982) and recorded as $cm^2\ cm^{-3}$. Due to the presence of gaps and wood layers in both cores (Figure S1), contiguous sampling for macrocharcoal analysis was not possible. Thus, a total of 147 and 159 sub-samples were collected along the KP and KTG cores, respectively (see Supplementary S1 for detail sub-sample depth). The sub-samples were then prepared following the protocols in Rhodes (1998) and Stevenson and Haberle (2005). The OM in the sample was removed using weak hydrogen peroxide (6% H_2O_2) and particles >125 µm were retained after gentle wet-sieving. Under a stereomicroscope, all charcoal particles >150 µm were counted and recorded as particles cm^{-3}. Macro- and microcharcoal data were then analyzed using the calculation described by Cole et al. (2019) to isolate individual peaks which represent fire episodes (see Supplementary S2 for detail step). The visualization of the LOI, $\delta^{13}C_{org}$, pollen and spore, and charcoal data were done with the program C2 (Juggins, 2007).

2.3 | Methodological limitation

Palynology still is the most accurate and robust method to reflect past vegetation changes surrounding a core location to date (Julier et al., 2018). However, it needs to be noted that historical vegetation records relied heavily on the pollen deposition of largely anemophilous or wind-pollinated taxa with entomophilous Dipterocarpaceae, which are common PSF taxa and are usually underrepresented in the record (Gottsberger, 1999; Morley, 1981). Similarly, taxa with a thin pollen wall such as Lauraceae, which are also common in PSF, are also poorly present, because they are being destroyed by acetolysis treatment (Hesse et al., 1999). Thus, a lack or a low proportion of Dipterocarpaceae and Lauraceae pollen in both records should not be interpreted as absence or low abundance. Also, the dense and close PSF canopy would probably restrict long-distance transportation of pollen (Cole et al., 2015; Elenga et al., 2000). Please also note that although *Casuarina* is notably salt tolerant and typically grow on coasts (Anderson & Muller, 1975; Sosef et al., 1998), it can also be found in different altitudes and on *kerangas* and peat swamp forest (Anderson & Muller, 1975; Anshari et al., 2001, 2004). Due to difficulties to palynologically separate *Casuarina* to species level, the “inland” species, for example, *C. nobile* and *C. junghuhniana*, are likely included in the MMA group.

3 | RESULTS

The 910 cm long KTG core consists of 830 cm organic and peat layer overlying white kaolinite basal clay. It is a coarse peat, rich in fabric material and with small and large woody fragments, except for the bottom-most part, where the peat is fine and mixed with mineral material. A layer of fresh wood and void present at the depth of 149–168 cm (Figure S1). The KTG core comprises a depositional history from 17,000 cal year BP to present.

The paleoecological records of the KTG and KP cores are each divided into five zones based on agglomerations of palynological data in a constrained cluster analysis (CONISS; Figure S3; Grimm, 1987). Detail results of pollen and spore, LOI, $\delta^{13}C_{org}$, and micro- and macrocharcoal analysis of KTG and KP cores are displayed in Figures 2–4 (see Table 1 for details).

Zone KTG 1 (17,000–10,800 cal year BP) is characterized by the domination of Poaceae, Cyperaceae and Asteraceae pollen (OV group; Figure 2a), whereas the PSF group dominates in zones KTG 2–5 (10,800 cal year BP to present). In zone KTG 3 (8700–5700 cal year BP), pollen of Rhizophoraceae, *Casuarina*, *Xylocarpus* and other MMA markedly increased, although PSF still dominant. The pollen of RP (e.g., *Pterocarpus*, *Ganophyllum*) and MXF (e.g., *Glochidion*, *Myrica*) group relatively stable throughout the record. Meanwhile, *Pinus* (LD group) occurred only occasionally.

The LOI values of zone KTG 1 range from 28% to 96%, reaching >50% toward the end of the zone (depth 817; ca. 11,500 cal year BP; Figure 3). The LOI values then remain above 96% in zones KTG 2–5. The average peat accumulation rates are highest in zones KTG 2 and 4 (0.9 and 1 mm year^{-1}), and lowest in zone KTG 5 (0.6 mm year^{-1}). In zone KTG 1, the $\delta^{13}C_{org}$ value is higher, fluctuating around −24‰. The values decrease at the end of the zone and remained below −27‰ throughout the record. Microcharcoal concentration and fire peaks are higher at the end of zone KTG 1 and the first half of KTG 2. Meanwhile, macrocharocal concentration and fire peaks are higher at the end of zone KTG 1, entire zone KTG 3 and the first half of zone KTG 4.

The 930 cm long KP core consists of 860 cm organic and peat layer overlying brown basal clay. The peat texture is coarse and rich in fabric and woody material except for the bottom part where the peat is clayey and fine. A very soft, highly decomposed wood layer is found at 788–830 cm, while a fresh wood and void layer is present at the depth of 20–84 cm (Figure S1). Radiocarbon dating results suggest that the KP core comprises a depositional history from 5100 cal year BP to present.

Zone KP 1 (5100–4790 cal year BP) is dominated by pollen of Rhizophoraceae, *Bruguiera*, *Casuarina*, *Aegiceras* (MMA group; Figure 2b). In zone KP 2 (4790–4250 cal year BP), MMA pollen decreased while pollen of *Thunbergia*, *Nepenthes*, Menispermaceae, Poaceae (OV group) and *Calophyllum*, *Campnosperma*, *Tristaniopsis*, *Pandanus* and *Ilex* (PSF group) markedly increase. The PSF domination characterizes zones KP 3–5 (4250 cal year BP to present). Pollen of *Timonius*, *Freycinetia* (RP group) and *Glochidion*, *Melicope* (MXF group) slightly increases in zone KP 3 (4250–3470 cal year BP) but remains low throughout the record, while *Pinus* occurred only occasionally.

The LOI values of zone KP 1 range from 28% to 90%. Toward the end of zone KP 1 (827 cm; ca. 4800 cal year BP), the LOI values reached >80%. It then remains above 95% in zones KP 2–5. The average peat accumulation rates are highest in zone KP 2 (2.2 mm year^{-1}) and remain relatively stable at around 1.4 mm year^{-1} with an increase in the first half of zone KP 5 to 1.6 mm year^{-1}. The $\delta^{13}C_{org}$ value is higher at the beginning of zone KP 1, fluctuating around −26‰. The values increase toward the end of the KP 1 and then fluctuates around −30‰ in zones KP 2–5. Micro- and macrocharocal concentration and macrocharcoal fire peaks are higher in zone KP 4 and the first half of KP 5. Microcharcoal fire peaks are higher at the start of zone KP 2 and is lower and relatively stable in zones KP 3–4. In KP 5, microcharcoal fire peaks increase toward the end of the zone.

4 | DISCUSSION

4.1 | Development of the Katingan and Kampar peatlands

Despite being located in the coastal area, the Kampar Peninsula and Katingan peatlands initiated in different periods and in different environmental conditions (Figures 2–4). The accumulation of OM

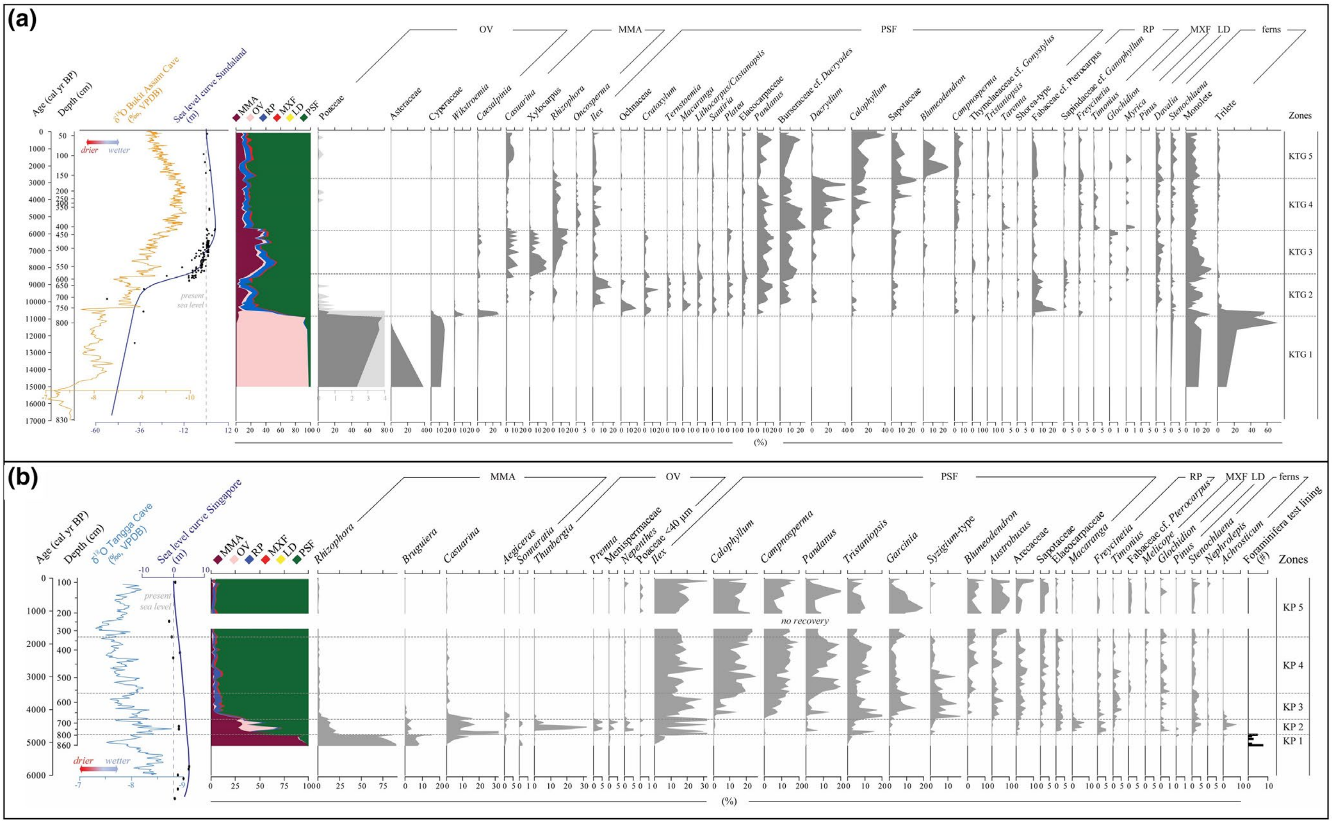

FIGURE 2 Pollen diagram of selected taxa recorded from (a) the KTG core from Katingan, Borneo and (b) the KP core from Kampar Peninsula, Sumatra. The results are compared with: paleoprecipitation record from Bukit Assam, Gunung Buda, Sarawak (Chen et al., 2016) and the reconstructed sea level curve from Sundaland (Bird et al., 2007, 2010; Geyh et al., 1979) for KTG core; paleoprecipiation record from Tangga Cave, West Sumatra (Wurtzel et al., 2018) and sea level curve from Singapore (Bird et al., 2007, 2010) for KP core. Pollen group elaborations are provided in Section 2.2. Complete list of taxa recorded is available in Supplementary S3

in Katingan started around 17,000 cal year BP and the peat (OM >50%; Wüst et al., 2003) started to form around 11,600 cal year BP (Table 1; Table S1). Pollen data suggest that the ecosystem was dominated by Poaceae, Cyperaceae, Asteraceae and Lycopodiaceae (Figure 2a) with a small proportion of *Gonystylus* during this time. The domination of grasses and herbs is also supported by the $\delta^{13}C_{org}$ value that ranges from −17.8 to −24‰ (average −22.4‰), which suggests C4 plants as the main source (Cheng et al., 2013; Kohn, 2010). This further supports the presence of a savanna-like environment in Sundaland (Bird et al., 2005; Morley, 1981; Wurster et al., 2019). Our findings are in accordance with those of other studies, that the peatlands in Central Kalimantan developed mainly after 15,000 cal year BP, overlying a white, quartz podzol plain that is essential in forming a perched water table for peat accumulation (Dommain et al., 2011; Neuzil, 1997; Page et al., 2004; Sieffermann et al., 1987, 1988).

Meanwhile, the accumulation of OM on the Kampar Peninsula started at 5100 cal year BP and the peat started to form at 4900 cal year BP (Table 1; Table S1). The ecosystem was dominated by mangrove vegetation as indicated by the dominance of *Rhizophora*, *Aegiceras* and *Bruguiera* pollen (Figure 2b) and the $\delta^{13}C_{org}$ ranging between −30‰ and −26‰ (Figure 3; Jennerjahn et al., 2021; Rodelli et al., 1984). Foraminifera test-lining also present at this stage (Figure 2b) corroborates the direct marine influence on the site during the time of deposition (Mathison & Chmura, 1995). Altogether, the evidence suggests that the Kampar Peninsula peatland developed on a mangrove sediment. The development of the Kampar peatland inferred from our data is in line with findings of a previous study, which concluded that peatland development in the coastal lowlands of Riau started around 6500–5000 cal year BP and had formed over mangrove sediments, based on the findings of black bark fragments (Fujimoto et al., 2019), presumably of *Avicennia*.

Despite similar distances from the shore of these two coastal peatlands, only the Kampar peatland developed over a mangrove swamp. The finding is apparent since the base elevation of the Kampar peatland (6 ± 4 m a.s.l.) is near the sea level, while that of the Katingan (19 ± 4 m a.s.l.) was well above it during its initiation period (−100 m; Dommain et al., 2014). The successional pattern of the Kampar peatland is similar to that of the "Anderson model" (Anderson & Muller, 1975), where mangrove vegetation was replaced by Myrtaceae *Campnosperma*, *Pandanus*, *Garcinia*, *Ilex*, *Calophyllum* and Sapotaceae. However, it does not show a succession via a *Shorea*-dominated phase with clear separation of different community assemblies (Phasic community 1–5) toward a stunted *Combretocarpus* forest (Phasic community 6) as in the "Anderson model," possibly due to different ecological conditions, for example, precipitation, seasonality, microtopography or due to species distribution range. Meanwhile, the onset

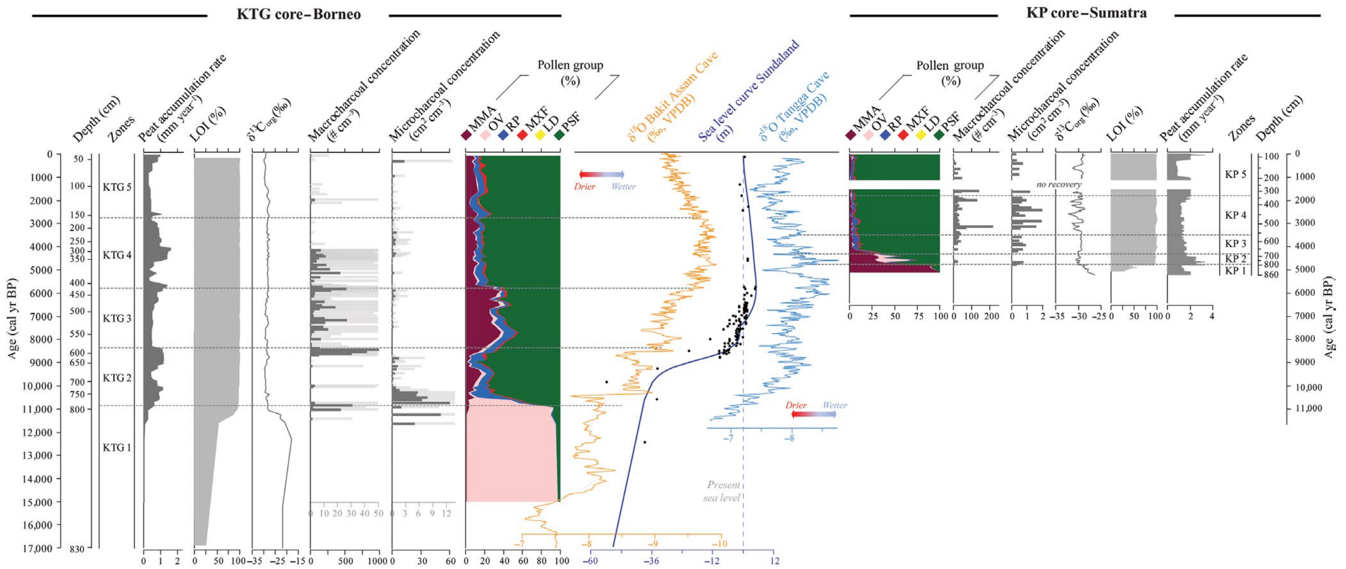

FIGURE 3 Records of LOI, $\delta^{13}C_{org}$, and micro- and macrocharcoal analysis of KTG (left) and KP (right) cores. The results are compared with paleoprecipiation record from Bukit Assam, Gunung Buda, Sarawak (Chen et al., 2016 for KTG), Tangga Cave, West Sumatra (Wurtzel et al., 2018 for KP) and sea level curve from Sundaland (Bird et al., 2007, 2010; Geyh et al., 1979). Pollen group elaborations are provided in Section 2.2

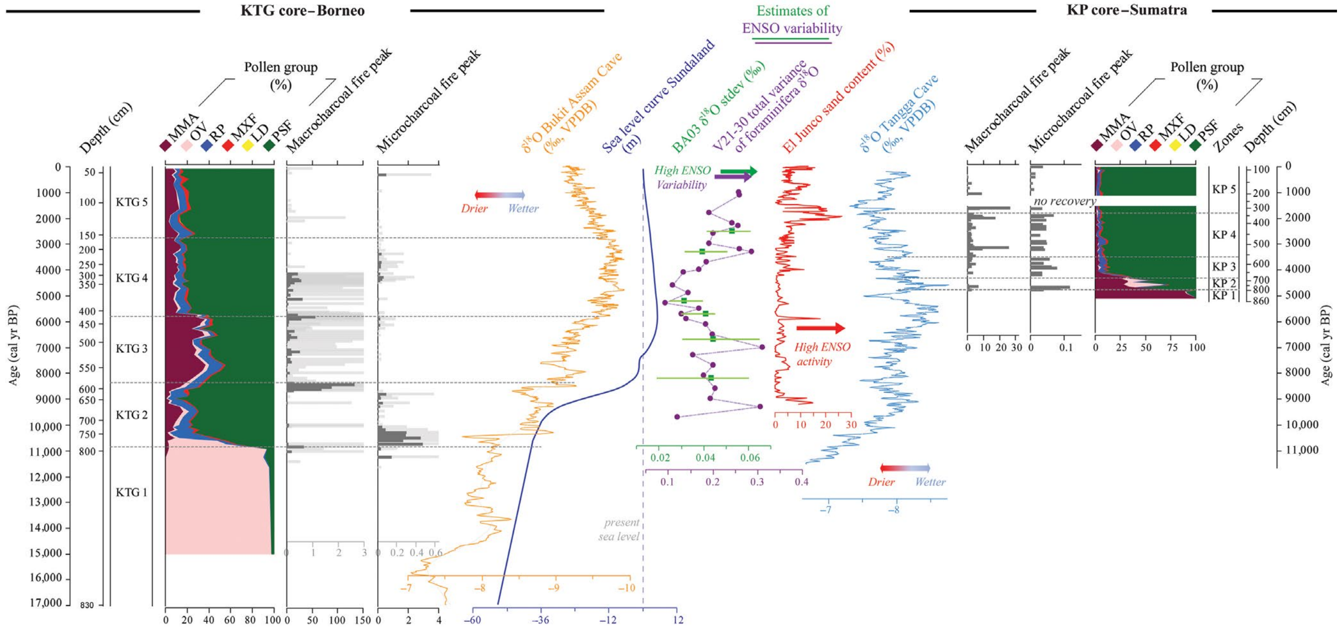

FIGURE 4 Records of and micro- and macrocharcoal analysis of KTG (left) and KP (right) cores compared with paleoprecipitation record from Bukit Assam, Gunung Buda, Sarawak (Chen et al., 2016), Tangga Cave, West Sumatra (Wurtzel et al., 2018), sea level curve from Sundaland (Bird et al., 2007, 2010; Geyh et al., 1979), ENSO activity inferred from Lake El Junco sand content record (Conroy et al., 2008) and ENSO variability estimates from Bukit Assam speleothem record, Sarawak (Chen et al., 2016) and foraminifera record from eastern equatorial Pacific (Koutavas & Joanides, 2012). Pollen group elaborations are provided in Section 2.2

of OM accumulation in Katingan is rather similar to the neighboring Sebangau and Nee Soon peatlands in Singapore (Morley, 1981; Taylor et al., 2001). This further confirms that there are variations in the genesis of SE Asian coastal peatlands. The results also suggest that peat formation could start in an environment with any type of vegetation cover, as long as there is enough moisture available to prevent OM decay, that is, water saturated or inundated.

4.2 | Responses of the coastal peatlands to precipitation changes

The records from both peatlands are compared to the paleoprecipitation data from Bukit Assam, Gunung Buda, Sarawak (Chen et al., 2016), Tangga Cave, West Sumatra (Wurtzel et al., 2018). Both records, apart from being the only paleoprecipitation records

TABLE 1 Detail results of pollen and spore, LOI, C_{org}, $\delta^{13}C_{org}$, and micro- and macrocharcoal analysis of KTG and KP cores

Core	Zonation (depth and age)	Pollen and spore assemblage*	OM	Peat acc. rate	C_{org}	$\delta^{13}C_{org}$	Charcoal
KTG core Katingan, Central Kalimantan, Borneo	KTG 1 790–830 cm 10,800–17,000 (10,500–17,300) cal year BP	5% PSF (e.g., *Ilex*, *Calophyllum*, *Lithocarpus*/*Castanopsis*, Elaeocarpaceae, Thymelaeaceae cf. *Gonystylus*, Burseraceae cf. *Dacrycarpus*); 93% OV (e.g., Poaceae, Cyperaceae, Asteraceae); 2% MMA (e.g., Rhizophoraceae, *Casuarina*, *Xylocarpus*); <1% RP (e.g., Fabaceae cf. *Pterocarpus*, Fabaceae cf. *Ganophyllum*); 0% MXF (e.g., *Glochidion*, *Myrica*)	66 (28–96) %	0.2 (0.1–0.7) mm $year^{-1}$	15.7 (5–46.4) %	−23.8 (−17.8 to −28.5) ‰	macrocharcoal (MaChar) concentration 141.4 (31–615) particle cm^{-3}; microcharcoal (MicChar) concentration 23 (6.1 – 51.3) cm^{-2} cm^{-3}
	KTG 2 595–790 cm 8500–10,800 (8250–11,000) cal year BP	71% PSF (▲); 7% OV (▼); 7% MMA (▲); 13% RP (▲); 2% MXF (↔)	>96 (96–100) % (▲)	0.9 (1–1.1) mm $year^{-1}$ (▲)	58.3 (32.6–82.9) % (▲)	−28.6 (−27.3 to −30) ‰ (▼)	MaChar conc. 46.3 (1–823) particle cm^{-3} (▼); MicChar conc. 11.4 (0.3–60.7) cm^{-2} cm^{-3} (▼)
	KTG 3 425–595 cm 5800 – 8500 (5700 – 8700) cal year BP	58% PSF (▼); 3% OV (▼); 31% MMA (▲); 7% RP (▼); 2% MXF (↔)		0.7 (0.8–1) mm $year^{-1}$ (▼)			MaChar conc. 172.8 (3–1222) particle cm^{-3} (▲); MicChar conc. 1.2 (0.7–3.5) cm^{-2} cm^{-3} (▼)
	KTG 4 175–425 cm 2800–5800 (2600–5900) cal year BP	80% PSF (▲); 1% OV (↔); 11% MMA (▼); 6% RP (↔); 1% MXF (↔)		1 (1.3–1.3) mm $year^{-1}$ (▲)			MaChar conc. 59.9 (1–442) particle cm^{-3} (▼); MicChar conc. 1.7 (0.3–4.7) cm^{-2} cm^{-3} (▲)
	KTG 5 0–175 cm 0–2800 (−68 to 3000) cal year BP	82% PSF (↔); 1% OV (↔); 8% MMA (▼); 7% RP (↔); 3% MXF (↔)		0.6 (0.6–1.4) mm $year^{-1}$ (▼)			MaChar conc. 7.8 (1–69) particle cm^{-3} (▼); MicChar conc. 1.9 (0.4–13.4) cm^{-2} cm^{-3} (▲)

TABLE 1 (Continued)

Core	Zonation (depth and age)	Pollen and spore assemblage*	OM	Peat acc. rate	C_{org}	$\delta^{13}C_{org}$	Charcoal
KP core Kampar Peninsula, Riau, Sumatra	KP 1 790–930 cm 4790–5100 (4700 - >5600) cal year BP	4% PSF (e.g., *Ilex*, *Calophyllum*, *Campnosperma*, *Tristaniopsis*, *Pandanus*); <1% OV (e.g., *Thunbergia*, *Nepenthes*, Menispermaceae, Poaceae); 95% MMA (e.g., Rhizophoraceae, *Bruguiera*, *Casuarina*, *Aegiceras*); <1% RP (e.g., *Timonius*, *Freycinetia*): <1% MXF (e.g., *Glochidion*, *Melicope*)	49 (20–91) %	1.7 (1.2–2.9) mm year^{-1}	28.5 (8.5–57.8) %	−27.9 (−26 to −30.4) ‰	macrocharcoal (MaChar) concentration 0.2 (0–2) particle cm^{-3}; microcharcoal (MicChar) concentration 0 cm^{-2} cm^{-3}
	KP 2 675–790 cm 4250–4790 (4050–4900) cal year BP	44% PSF (▲); 11% OV (▲); 40% MMA (▼); 4% RP (▲); 1% MXF (↔)	>97 (93–100) % (▲)	2.2 (2.1–3.1) mm year^{-1} (▲)	56.2 (34–64.1) % (▲)	−29.7 (−27.9 to −34.2) ‰ (▼)	MaChar conc. 3 (0–25) particle cm^{-3} (▲); MicChar conc. 0.16 (0–0.78) cm^{-2} cm^{-3} (▲)
	KP 3 560–675 cm 3470–4250 (3225–4450) cal year BP	86% PSF (▲); <1% OV (▼); 5% MMA (▼); 6% RP (↔); 2% MXF (↔)		1.4 (1.6–1.7) mm year^{-1} (▼)			MaChar conc. 24.5 (0–221) particle cm^{-3} (▲); MicChar conc. 0.3 (0–0.9) cm^{-2} cm^{-3} (▲)
	KP 4 355–560 cm 1890–3470 (1700–3700) cal year BP	92% PSF (▲); <1% OV (↔); 2% MMA (▼); 4% RP (↔); 2% MXF (↔)					
	KP 5 0–355 cm 0–1890 (−68 to 2100) cal year BP	94% PSF (↔); <1% OV (↔); 1% MMA (↔); 3% RP (↔); 2% MXF (↔)		1.6 (1.8–2.2) mm year^{-1} (▲)			MaChar conc. 11 (0–142) particle cm^{-3} (▼); MicChar conc. 0.21 (0–1.07) cm^{-2} cm^{-3} (▼)

Note: The values given are averages. The numbers in brackets represent the data value range, except for the age and peat accretion rate where the interval values based on the Bayesian age model uncertainty envelopes are shown. Results are visualized in Figure 5.

▲: value increase; ▼: value decrease; ↔: value relatively stable; *: pollen group abbreviation (see Section 2.2).

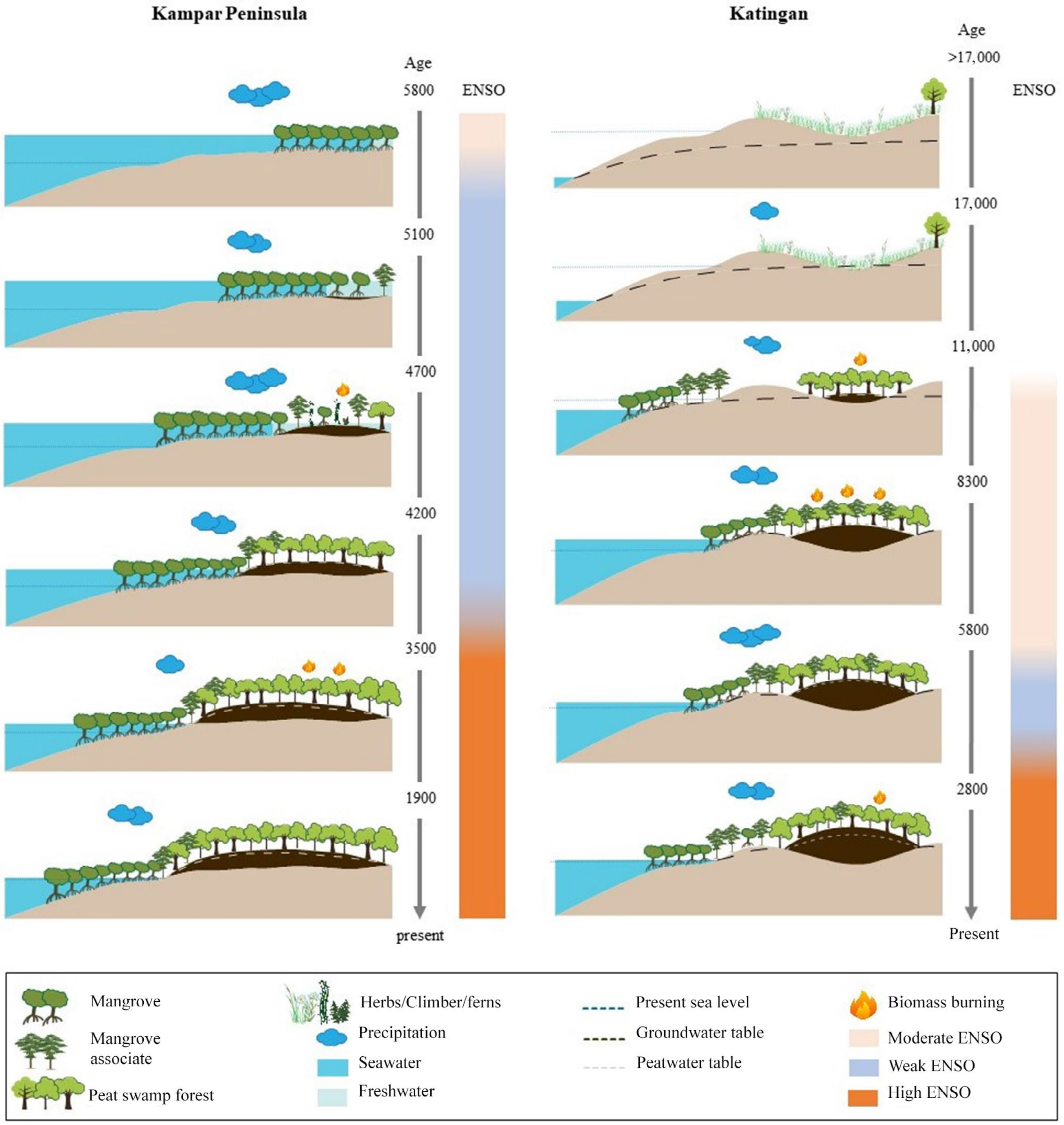

FIGURE 5 Cartoon simplifying the initiation and evolution of the Kampar Peninsula peatland in Riau, eastern Sumatra (left), and the Katingan peatland in Central Kalimantan, southern Borneo (right), according to the palynological zones of KP and KTG (correspond to Table 1). Note that only local fire episodes (inferred from macrocharcoal data) are depicted here. The ages are in cal year BP

available in Borneo and Sumatra, generally represent the regional precipitation trends. In Indonesia, the annual precipitation patterns are mainly controlled by the Intertropical Convergence Zone (ITCZ), in addition to other factors (e.g., Asia-Australia monsoon, ENSO, Indian-Ocean-Dipole) (Abram et al., 2009; Aldrian & Susanto, 2003; Denniston et al., 2016; Saji et al., 1999). The ITCZ latitudinal position that is strongly correlated with the monsoons (Cheng et al., 2012; Mohtadi et al., 2016), however, changed seasonally and during abrupt climate changes (Figure 1); it migrated southward during the Heinrich Stadial (HS) and the Younger Dryas, and northward during the Antarctic cold reversal (Kuhnt et al., 2015). Therefore, caution should be exercised when comparing the records from Katingan with Gunung Buda, because they are located at different latitudes (Figure 1).

4.2.1 | The Katingan peatland

The onset of OM accumulation in Katingan coincided with HS1 (18,000–15,000 cal year BP) (Carolin et al., 2013; Wang et al., 2008), which suggests a high moisture level during that time. However, the Gunung Buda speleothem recorded lower precipitation during HS1 (Figure 2; Carolin et al., 2013; Chen et al., 2016; Partin et al., 2007), in agreement with the northern hemisphere records in Hulu Cave, China (Wang et al., 2008), and the Sulu Sea, Philippines (Dannenmann et al., 2003). The accumulation of OM in Katingan thus suggests that southern Borneo was still located within the ITCZ rain belt during the HS1 despite its southward migration (Figure 1). Furthermore, the Asian monsoon reportedly strengthened during HS1 and resulted in wetter conditions in the Australian-Indonesian monsoon region, where the KTG core is located (Mohtadi et al., 2016; Muller et al., 2012).

In the Early Holocene, the decreasing δ^{18}O in Bukit Assam Cave, Borneo and Tangga Cave, West Sumatra suggests a general precipitation increase in Indonesia (Chen et al., 2016; Wurtzel et al., 2018). During this transitional period from dry to wet (though still mostly dry; Figure 3), around 11,000–10,500 cal year BP, local fire episodes in Katingan increased and were subsequently followed by elevated regional burning. In such a transition, higher moisture availability during a wet period probably fostered higher biomass, hence, fuel loading in Katingan and resulted in larger fire in the following dry period (Jensen et al., 2018). The increase in local fire episodes, however, did not seem to interrupt the peat accretion and PSF establishment in Katingan (Figure 3).

At 10,500 cal year BP, precipitation in Borneo increased and the pollen data and a low $\delta^{13}C_{org}$ value (average −28‰), indicating mainly a C3 plant source (Kohn, 2010), suggest that the grass-dominated ecosystem was replaced by PSF (Figures 2a and 5). The development of PSF in Katingan was pioneered by *Wikstroemia*, *Caesalpinia* and Fabaceae cf. *Pterocarpus* (Brink & Escobin, 2003; Lemmens & Wulijarni-Soetjipto, 2003; Thomson, 2006) that commonly grow in open areas or at forest edges. It was then later dominated by *Ilex*, Burseraceae cf. *Dacryodes*, *Macaranga* and *Cratoxylum*, which are also PSF pioneer vegetation, in particular after fires (Eichhorn, 2006). Following the increased precipitation and PSF establishment, the local fire episodes in Katingan notably decreased (Figure 3; Table 1).

Precipitation in Borneo continued to increase throughout the Early Holocene (Figure 3; Table 1). This, together with the continuously rising sea level (discussed in detail in Section 4.3) likely led to waterlogged conditions in Katingan, which allowed peat to accumulate rapidly (Dommain et al., 2011, 2014). The peat accumulation of Katingan, however, then decreased from 8500 to 5800 cal year BP (Figure 3; Table 1). Continuously increasing precipitation in Borneo throughout the Middle-Late Holocene accompanied by SLR to its Mid-Holocene highstand (see Section 4.3) probably resulted in a very high water table to the extent that it could have reduced the ecosystem productivity, hence, slowed the peat accretion down (Limpens et al., 2008; Mezbahuddin et al., 2014). Meanwhile, ENSO was moderately active in the Mid-Holocene (Figure 4; Chen et al., 2016; Koutavas & Joanides, 2012), which coincided with frequent local fire episodes in Katingan (from 8800 to 4200 cal year BP; Figure 3). In addition to other factors (see Section 4.3), the Mid-Holocene ENSO possibly played a role in enhancing dry fuel (aboveground biomass) availability during dry El Niño events (Hapsari et al., 2021). Moreover, lightning hazards, a natural ignition source in tropical humid forests (Krasovskii et al., 2018; Tutin et al., 1996), increased during El Niño events over land and coasts in Indonesia (Dowdy, 2016; Hamid et al., 2001). During El Niño, an increase in air surface temperature and a larger sea-land temperature contrast can trigger the formation of deep convective storms, thus, produce more lightning discharge (Hamid et al., 2001). Lightning-related fires have been observed to burn tree crowns and trunks in humid tropical forest, but they rarely spread beyond the immediate strike area and typically went out due to lack of dry fuel (Tutin et al., 1996; Wade et al., 1980).

Between 5800 and 3000 cal year BP, the Gunung Buda speleothem shows minimum δ^{18}O values (Figures 2a–4), indicating maximum precipitation (Chen et al., 2016). This probably allowed *Dacrydium*, a taxon preferring very wet conditions (Morley, 2011), to expand and become dominant in Katingan (Figure 2a). Such convective maximum also led to less local fire episodes in the Katingan peatland (Figure 3; Table 1). A *Dacrydium*-dominant phase is also recorded in the neighboring Sebangau peatland record (Morley, 1981) that, although the record is without chronology, possibly occurred at the same time during the very wet period in Borneo. Morley (1981) suggested that the *Dacrydium* domination in southern Kalimantan might represent a transitional phase from the mixed swamp to the *padang* forest (species-poor pole forest on deep peat).

After 3000 cal year BP, precipitation in Borneo decreased as suggested by a higher δ^{18}O value in Bukit Assam Cave. This possibly caused *Dacrydium* to decrease in the Katingan peatland and allowed the expansion of *Calophylum*-Sapotaceae-*Blumeodendron*, which prefer a wet but non- or only seasonally inundated environment (Sosef et al., 1998; van Royen, 1960). Less precipitation in Borneo in the Late Holocene was also accompanied by a more active ENSO (Chen et al., 2016), which likely led to increased local burning in Katingan after 2000 cal year BP, as suggested by an increased macrocharcoal concentration and fire peaks (Figure 3; Table 1). Reduced precipitation in the Late Holocene also likely led to a peatland water table drawdown, which enhanced OM decomposition (Cobb et al., 2017; Mezbahuddin et al., 2015; Page et al., 2009) and resulted in a lower peat accumulation rate in Katingan (Figure 3; Table 1).

4.2.2 | The Kampar peatland

Following a sea level regression, the Kampar peatland initiated at 5100 cal year BP (Section 4.3). At 4800 and 4200 cal year BP, the Tangga Cave speleothem recorded minimum δ^{18}O values (Figures 2b–4), indicating periods of high precipitation (Wurtzel et al., 2018). Such high precipitation, in addition to a still higher-than-present sea level (Section 4.3), probably promoted waterlogged conditions that were suitable for rapid peat accumulation on the eastern coastal plain of Sumatra (Dommain et al., 2011).

In Sumatra, precipitation decreased between 4200 and 1800 cal year BP (Figures 2b–4) (Wurtzel et al., 2018). This coincided with higher macro- and microcharcoal concentrations and fire peaks in the Kampar Peninsula record (Figures 3 and 4; Table 1), indicating a period with increased local and regional burning, respectively. Such relatively dry climate, accompanied by a high ENSO activity in the Late Holocene (Chen et al., 2016; Conroy et al., 2008; Koutavas & Joanides, 2012) possibly promoted the availability of dry fuel and natural ignition source (see Section 4.2.1) in the Kampar Peninsula peatland. Increased fire occurrence in peatlands related to the Late Holocene ENSO intensification has also been well documented elsewhere in SE Asia (Anshari et al., 2001; Cole et al., 2015; Hapsari et al., 2021). The continuously accumulating peat in Kampar indicates that the peatland must have been permanently wet and suggests that the occurred fires only burnt the vegetation. Moreover, lightning-induced forest fire typically only has limited impact on humid forest (see Section 4.2.1).

The decrease in precipitation in Sumatra, however, possibly had little impact on the water table lowering in the Kampar Peninsula considering a still higher-than-present sea level (Section 4.3). This possibly favored the growth of PSF dominated by *Ilex*, *Tristaniopsis*, *Garcinia* and *Syzigium* (Figure 2b), taxa adaptable to poor drainage conditions and frequent floods (Basak et al., 2015; Sosef et al., 1998). The continuously decreasing precipitation (Wurtzel et al., 2018), in combination with a further regressing sea level (Section 4.3) promoted a vegetation shift on the Kampar Peninsula after 3500 cal year BP to *Pandanus*, *Calophyllum* and *Campnosperma* (Figure 2b), taxa which are preferring non- or only seasonally inundated conditions (Sosef et al., 1998). This PSF composition resembles the present-day pole forest vegetation present in Sumatra (Brady, 1997; Gunawan et al., 2012).

In the period 2300–1500 cal year BP, the Tangga Cave speleothem recorded maximum δ^{18}O values, indicating the driest period in Sumatra since the Mid-Holocene (Wurtzel et al., 2018). During this period, however, the peat accumulation rate on the Kampar Peninsula slightly increased. Lowered precipitation during this period possibly led to an optimum water table depth for the covering vegetation, hence promoted their productivity (Mezbahuddin et al., 2014, 2015). A study in a coastal forest in Brazil shows that under waterlogged conditions, *Calophyllum* produces 30% and 50% less root and leaf biomasses, respectively (de Oliveira & Alfredo, 2010).

After 1800 cal year BP, rainfall in Sumatra increased (Wurtzel et al., 2018), which possibly promoted the expansion of *Garcinia* and *Austrobuxus* in the Kampar Peninsula peatland, for these taxa require a high amount of precipitation (Floyd & Poropat, 2008; Pramanik et al., 2018). During this time, the macrocharcoal concentration and the fire peaks decreased in the Kampar Peninsula record (Figures 3 and 5), which indicates less local burning and fire episodes. The wetter conditions after 1800 cal year BP possibly limited the dry fuel availability in the Kampar Peninsula PSF.

4.3 | Responses of the Katingan and Kampar Peninsula peatlands to sea level changes

From the Last Deglaciation to the Early Holocene, sea level in Sundaland rose rapidly (Geyh et al., 1979; Sathiamurthy & Voris, 2006). This likely caused an impeded drainage and rising groundwater level in the areas of present-day Borneo, Sumatra and the Malaysia Peninsula (Sathiamurthy & Voris, 2006; Surya et al., 2019). In combination with increasing precipitation in Borneo (Section 4.2.2), it led to waterlogged conditions in Katingan, which allowed peat to accumulate rapidly (Dommain et al., 2011, 2014).

The sea level then stabilized when it almost reached the present level by around 8500 cal year BP (Geyh et al., 1979; Sathiamurthy & Voris, 2006). During this time, an extensive mangrove forest was established in southern Borneo as indicated by an increase in MMA pollen in the Katingan record (Figure 2a). Prior to this period, while the sea level was rising, the sediment from the East Sunda rivers, such as the Paleo-Kahayan or the Paleo-Seruyan (Voris, 2000), possibly accumulated in the present-day southern coastal plain of Borneo. It possibly created a shoaling estuary suitable for mangrove colonization once the sea level stabilized as, for example, observed in northern Australia (Woodroffe et al., 1985). The continuously rising sea level to its Mid-Holocene highstand (4–5 m above the present level) (Bird et al., 2007, 2010; Sathiamurthy & Voris, 2006) likely led to a landward migration of mangrove zones (Yao & Liu, 2017) and subsequently resulted in an encroachment of mangroves and their associate vegetation in the Katingan peatland (Figure 2a; Table 1).

Although tolerating acidic conditions and having physiological adaptation to waterlogged environment, that is, stilt and buttress roots and pneumatophores, much like the PSF trees, there is no record of mangrove trees growing on ombrotrophic peatland nowadays. From the Miocene age, however, an increasing proportion of mangrove pollen on a PSF dominated environment identical to modern PSF is obtained from the mid-section of a very thick (>15 m) coal deposit from Southeast Kalimantan (Morley, 2013). As thick coal deposits generally have similar properties (ash and sulfur content) with modern ombrotrophic peat deposits (Wüst & Bustin, 1999), it suggests a possibility of mangrove encroachment on an ombrotrophic peat setting.

In northern Australia, mangrove was able to encroach into the *Melaleuca* swamp only after saltwater intruded the freshwater environment (Cobb et al., 2007). Mangroves are obligate halophytes, that is, they require salt to grow and thrive, although they can survive in freshwater for a limited time (Basyuni et al., 2021; Nguyen et al., 2015; Wang et al., 2011). The absence of mangrove on peatlands might be related to its low salinity (typically <1 psu; Sabiham, 2010) that limits its ability to compete with other freshwater taxa. A concurrent landward shift of the intertidal zone following SLR possibly resulted in salinity increase through various mechanisms (Herbert et al., 2015) and accommodated mangrove encroachment into a freshwater peatland.

The possibility of mangrove encroachment is also discussed in the study of the neighboring Sebangau record, where the proportion mangrove pollen increased in the mid-section of the core (Morley, 1981). The proportion of mangrove pollen in Sebangau, however, was much lower and it was inferred that the mangrove strip was probably closing in, but did not encroach the area and that the pollen was possibly transported through wind or tidal wave (Morley, 1981). Unlike the Katingan record, however, the Sebangau core was retrieved 100–130 km away from the coast, which most likely explains the discrepancy between the two neighboring records.

During the sea level highstand at 5700 cal year BP (Bird et al., 2007, 2010), however, the absence of foraminifera test-lining in the record suggests that the Katingan peatland did not have a direct marine influence (Mathison & Chmura, 1995). This is further confirmed by a $\delta^{13}C_{org}$ value in the Katingan peat record that remains above −28‰, suggesting limited organic input from marine sources (Kusumaningtyas et al., 2019; Rodelli et al., 1984). The sea level transgression map of the Sunda Shelf also shows that the shoreline of modern Central Kalimantan was not pushed far inland due to its relatively high elevation (>5 m a.s.l.; Figure 1) (Dommain et al., 2014; Sathiamurthy & Voris, 2006).

From 8800 to 4200 cal year BP, that is, the period of mangrove encroachment, local fire episodes in Katingan were frequent (Figure 3), which was partly related to the moderately active ENSO in the Mid-Holocene (see Section 4.2.2). Mangrove woods are of high calorific value and burn long and hot (Gajula et al., 2020). *Casuarina*, in particular, can even be burned when green (National Research Council, 1984). The abundance of more combustible vegetation in Katingan during this period thus probably promoted the more frequent local fire episodes.

Moreover, possible salt toxicity due to salinity increase during this period, as suggested by mangrove encroachment, likely resulted in lower leaf water content (leaf scorch) and higher mortality in most of the inland vegetation and other non-halophytes (Acosta-Motos et al., 2017; Bartha et al., 2015; de Sedas et al., 2019). Widespread dieback of *Melaleuca* swamp, for example, was observed following saltwater intrusion in northern Australia (Cobb et al., 2007). Only very few PSF species are known to be salt tolerant (Santos et al., 2016); thus, an increased salinity likely contributed to a higher availability of dry aboveground fuel, that is, dried or dead tree leaves and branches, in the Katingan peatland during the period 8800 to 4200 cal year BP.

Furthermore, salt toxicity led to lower growth rate, stem height and leaf area of tropical inland vegetation (de Sedas et al., 2020). This might have also resulted in a lower PSF canopy cover, hence lower air humidity, a major factor in preventing fire spread in peatland ecosystems (Cole et al., 2015). Also, the air humidity of mangrove forests (<50%) is reportedly lower than that of PSFs (>80%) (Anamulai et al., 2019; Kaunang & Medellu, 2013). It insinuates a sparser canopy cover of mangrove trees compared to the PSF, although further study is needed to confirm this.

A similar observation was reported from Batu Niah, Sarawak (Cole et al., 2015). There, the local fires were frequent at the time when mangrove taxa were abundant despite very wet conditions (ca. 4000–7000 cal year BP) (Chen et al., 2016). This further strengthens the possible relation between more frequent and severe fires (i.e., higher consumption of fuel as suggested by higher fire peaks; Dunnette et al., 2014; Keeley, 2009) with (i) increased abundance of high calorific value fuel/biomass; (ii) higher fuel availability induced by salt toxicity and (iii) a lower forest canopy cover.

After the Mid-Holocene highstand, the sea level started to regress slowly and reached the present level at 1000 cal year BP (Bird et al., 2007, 2010). This likely led to a seaward migration of the shoreline and the mangroves, as evident from the lower pollen proportion of mangroves and their associate taxa in Katingan (Figure 2a). The continuously accumulating peat in Katingan in the late Holocene seems in contrast with the widespread cessation of peat accumulation in Central Kalimantan after 2500 cal year BP and has since been decomposing. Old ages near surface are reported from several peat profiles from the neighboring deposits, for example, on the eastern side of the Katingan river (hereafter called the Rungan peatland) (Sieffermann et al., 1987, 1988). Sea level regression followed by reduced precipitation has resulted in lowered water tables in this peatland, and thus restricted peat accretion and promoted peat decay (Dommain et al., 2011, 2014; Sieffermann et al., 1988).

However, the widespread peat accumulation cessation in the Rungan peatland was seemingly restricted to the “high peat” area, that is, with >35 m a.s.l. basal elevations (Dommain et al., 2014; Sieffermann et al., 1988). The Katingan peatland was most likely exempted from the “cessation spell” because it is located on a much lower basal elevation (19 ± 4 m a.s.l.). A similar exemption is displayed in Sieffermann et al.'s (1988) core P.9 taken from the same Rungan deposit, where the date at 3 m below surface is ca. 2900 cal year BP. Although unspecified, the core P.9 possibly also has a much lower basal elevation.

Similarly, a mangrove seaward migration was also recorded in the Kampar core after 4800 cal year BP, as indicated by less mangrove taxa and a higher proportion of taxa commonly growing landward of a mangrove forest (Figure 2b; Table 1) (Engelhart et al., 2007; Sefton & Woodroffe, 2021; Sosef et al., 1998; Woodroffe et al., 2016). The disappearance of foraminifera test-lining from the Kampar record afterwards also indicates that the site no longer received marine water input (Mathison & Chmura, 1995), which further confirms that the sea level was regressing at that time (Bird et al., 2007, 2010).

Simultaneously, a higher proportion of *Thunbergia*, *Nepenthes*, *Premna* and Menispermaceae in the Kampar record (Figure 2b) suggest that the site became more open. During that period, the finding of a layer of 40 cm decayed wood in the KP core (Figure S1) indicates the possibility of storm surges or windthrow. However, such disturbances do not commonly result in long-lasting canopy openness in mangrove forests, where recovery can occur only after 25 years (Baldwin et al., 2001; Imbert, 2018). Meanwhile, no information is available on whether mangrove progradation would leave behind a more open mudflat. At 4200 cal year BP, the PSF was established on the Kampar Peninsula.

The succession from mangrove forest to PSF was initially thought to be related to the accumulation of OM or peat leading to an acidic and nutrient-poor environment, in which mangrove species are unable to regenerate (Anderson & Muller, 1975). However, mangroves are able to form and grow on peat (Ellison, 2009; Ezcurra et al., 2016) as also seen in the Katingan record. Thus, it is more likely that PSF vegetation is unable to survive in a saline or brackish environment (Morley, 1981), and the development of a mature PSF on coastal peatlands was rather promoted by sea level regression that limited sea water intrusion. Multiple basal dates from the neighboring Siak peatland also suggest that the peat developed earlier inland (ca. 6500 cal year BP) and expanded seaward following sea level regression (Fujimoto et al., 2019).

The sea level regression was likely followed by a lowered water level of the adjacent ecosystem or bordering rivers (Hapsari et al., 2021), which determines the water table of the peatland and, hence, its subsequent peat accumulation capacity (Cobb et al., 2017). However, sea level was still between +2 and +3 m from 4200 to 3500 cal year BP (Bird et al., 2007, 2010). This probably helped keeping the water level of the adjacent ecosystems, bordering rivers, and thus also the peatlands, relatively higher then compared to the period after 1000 cal year BP (Hapsari et al., 2021).

4.4 | Early anthropogenic activities in the Katingan and Kampar Peninsula peatlands

Despite the potential natural origin of fires (Hapsari et al., 2021; Krasovskii et al., 2018), the presence or increase in charcoal or fire are often inferred to result from early anthropogenic activities (Anshari et al., 2001; Hope et al., 2005; Yulianto et al., 2004). To be able to distinguish between the two possible drivers, other evidence is required like, for example, archaeological or historical records, or an indication of anthropogenic disturbance that is commonly accompanied by pollen of agricultural taxa or a large quantity of pollen of open vegetation taxa (Hapsari et al., 2021).

An indication of anthropogenic forest opening or disturbance was largely absent in both the Katingan and Kampar Peninsula peatlands (Figure 2), even though cultural development in southern Borneo and Riau started to flourish at 4000 cal year BP and 1000 cal year BP, respectively (Indah et al., 2017; Kusmartono et al., 2017; Wiyanarti, 2018). This is in contrast with the apparent forest opening in the Sungai Buluh peatland in Jambi during the occupation period of the nearby Malayu Empire (Hapsari et al., 2017, 2018). Limited records of forest disturbance in Katingan and on the Kampar Peninsula in the past are possibly related to the remoteness of the core sites (around 6–16 km from river), which is similar to the findings in the Kutai peatland, where early human impact was more pronounced on more accessible sites near waterways (Hope et al., 2005).

5 | CONCLUSION

Despite being located in the coastal area, the Katingan and Kampar Peninsula peatlands initiated in different periods and environments (Figure 5). These records confirm that there are variations in the genesis of SE Asian coastal peatlands. It also suggests that peat formation could start on various substrates with various vegetation types, as long as there is sufficient moisture available to create water saturated condition or inundation that limit OM decomposition.

Changes in precipitation led to a PSF vegetation shift and different rates of peat accumulation in the Katingan and Kampar Peninsula peatlands (Figure 5). The results suggest that fire episodes in both peatlands generally correlated with shifting ENSO behavior throughout the Holocene and decreased precipitation in Borneo and Sumatra. Sea level changes also drove shifts in vegetation in both peatlands by mainly influencing the position of the mangrove forest.

The records show that anthropogenic activities were hardly relevant in the past, unlike the much larger scale effects of human activities today. Therefore, the observed environmental changes of the Katingan and Kampar Peninsula peatlands are almost exclusively attributable to natural drivers, mainly climate and sea level. This knowledge, in turn, can contribute to quantifying the contributions/relevance of natural variability vs. anthropogenic land use change for the various ecosystem functions and services (e.g., C storage, biodiversity) of peatlands. Once site conditions and data and resource availability allow the quantification of drivers and related effects during (past) times of little or no human impact, this knowledge, in combination with a quantitative assessment of present-day conditions with large-scale human impacts, may allow for a subtraction of the "natural" stressor effect and, hence, allow the quantitative evaluation of the "human" stressor effect. With regard to climate change outcomes, it still remains a challenge, because the large magnitude climate change of the past decades/century is a human-induced one. However, it may allow for the quantification of effects related to land use/cover change (LUCC), which, in turn, can provide a scale and therefore a more robust basis for environmental impact analysis and restoration efforts.

Our study demonstrates how the co-occurrence of multiple stressors on peatland ecosystems could have a greater impact than the sum of effects of their individual occurrence (Figure 6). Active ENSO, for example, resulted in a more frequent occurrence of low-severity fire by enhancing the availability of dry fuel and a natural ignition source (i.e., lightning). Meanwhile, SLR possibly led to increased salinity and related PSF (inland) vegetation injuries/mortalities, as well as to mangrove encroachment on coastal peatlands. When the two occurred simultaneously, they likely interacted synergistically and led to (i) increased abundance of high-quality fuel (i.e., mangrove wood); (ii) increased fuel availability induced by drought and salt-toxicity; (iii) lowered forest canopy cover, hence less humidity and (iv) an increase in natural ignition source, which resulted in occurrences of severe forest fires in pristine coastal peatlands.

It can be inferred that the future SLR, when interacting with continuing severe anthropogenic impact, for example, extensive PSF degradation, peatland drainage and intentional burning (Puspitaloka et al., 2021), will also possibly create synergistic negative impacts. Although SLR is predicted to increase peatland water tables and potentially leads to increased peat accumulation in healthy/intact ecosystems (Cobb et al., 2017), it will enable high-energy waves to

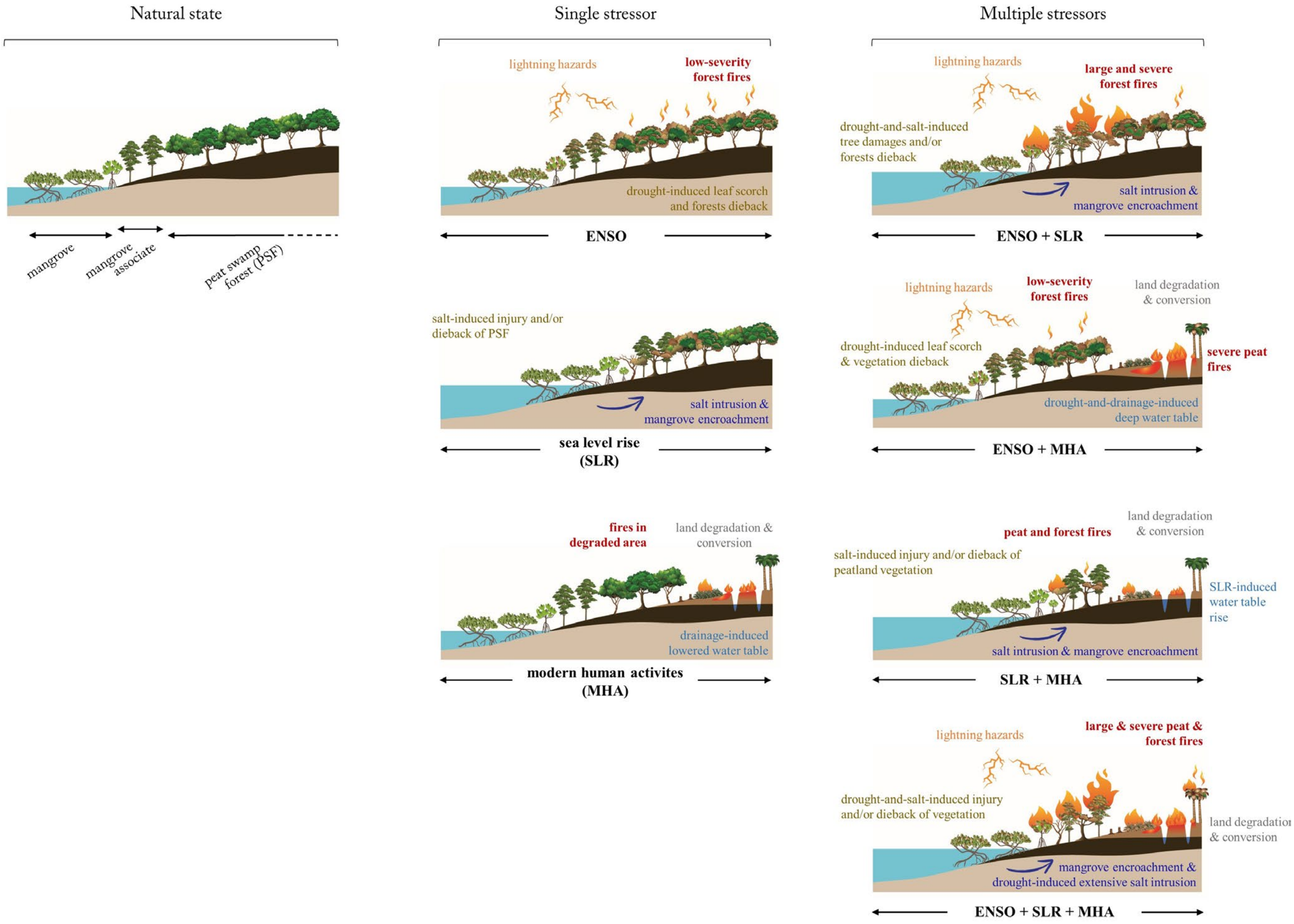

FIGURE 6 Schematic figure depicting the impacts of the occurrence of single and multiple stressors on coastal peatland ecosystems. Note that mangrove degradation, peat failure and peat subsidence are not included the depictions of the MHA and other subsequent inferences

reach farther up or inland thus exacerbating the already severe and/or initiate peat abrasion on coastal areas with severe mangrove degradation and subsequent peat failure/landslide such as in Bengkalis Island, Indonesia (Sutikno et al., 2017; Yamamoto et al., 2019). SLR is also predicted to result in widespread seawater inundation following subsidence in degraded and drained peatlands (Hoyt et al., 2020; Whittle & Gallego-Sala, 2016) and will foreseeably rapidly kill the freshwater PSF vegetation.

Along with the projected more frequent and more intense El Niños in the future (Freund et al., 2019; IPCC, 2021; Tangang et al., 2020), salt intrusion and its negative impact on freshwater vegetation will worsen and can reach farther inland (Herbert et al., 2015). This could contribute to a massive abundance of fuel that potentially promotes catastrophic and widespread forest fire events, even though the peat substrate itself might be protected from burning. Undoubtedly, this will elevate the level of carbon emissions from degraded and even some near-natural peatlands (Deshmukh et al., 2021), and therefore, accelerate global climate warming. With the sea level currently rising faster than ever, fire management in coastal peatlands must consider and anticipate such an additional risk that is, so far, unaccounted for.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

AUTHOR CONTRIBUTIONS

K. Anggi Hapsari led the manuscript writing. Tim Jennerjahn substantially contributed to the intellectual content. K. Anggi Hapsari and Tim Jennerjahn interpreted the data. K. Anggi Hapsari, Hermann Behling, Septriono Hari Nugroho and Eko Yulianto collected and analyzed the data. K. Anggi Hapsari, Septriono Hari Nugroho and Eko Yulianto arranged the fieldworks and permits. K. Anggi Hapsari and Hermann Behling obtained the funding. All authors critically contributed to the manuscript draft and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.941445) and Dryad (https://doi.org/10.5061/dryad.7pvmcvdvk; https://doi.org/10.5061/dryad.mpg4f4r1q).

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SUPPORTING INFORMATION

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