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Development and carbon sequestration of tropical peat domes in south-east Asia: links to post-glacial sea-level changes and Holocene climate variability

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ABSTRACT

Tropical peatlands of SE-Asia represent a significant terrestrial carbon reservoir of an estimated 65 Gt C. In this paper we present a comprehensive data synthesis of radiocarbon dated peat profiles and 31 basal dates of ombrogenous peat domes from the lowlands of Peninsular Malaysia, Sumatra and Borneo and integrate our peatland data with records of past sea-level and climate change in the region. Based on their developmental features three peat dome regions were distinguished: inland Central Kalimantan (Borneo), Kutai basin (Borneo) and coastal areas across the entire region. With the onset of the Holocene the first peat domes developed in Central Kalimantan as a response to rapid post-glacial sea-level rise over the Sunda Shelf and intensification of the Asian monsoon. Peat accumulation rates in Central Kalimantan strongly declined after 8500 cal BP in close relation to the lowering rate of the sea-level rise and possibly influenced by the regional impact of the 8.2 ka event. Peat growth in Central Kalimantan apparently ceased during the Late Holocene in association with amplified El Niño activity as exemplified by several truncated peat profiles. Peat domes from the Kutai basin are all younger than ~8300 cal BP. Peat formation and rates of peat accumulation were driven by accretion rates of the Mahakam River and seemingly independent of climate. Most coastal peat domes, the largest expanse of SE-Asian peatlands, initiated between 7000 and 4000 cal BP as a consequence of a Holocene maximum in regional rainfall and the stabilisation and subsequent regression of the sea-level. These boundary conditions induced the highest rates of peat accumulation of coastal peat domes. The Late Holocene sea-level regression led to extensive new land availability that allowed for continued coastal peat dome formation until the present. The time weighted mean Holocene peat accumulation rate is 0.54 mm yr^{-1} for Central Kalimantan, 1.89 mm yr^{-1} for Kutai and 1.77 mm yr^{-1} for coastal domes of Sumatra and Borneo. The mean Holocene carbon sequestration rates amount to 31.3 g C m^{-2} yr^{-1} for Central Kalimantan and 77.0 g C m^{-2} yr^{-1} for coastal sites, which makes coastal peat domes of south-east Asia the spatially most efficient terrestrial ecosystem in terms of long term carbon sequestration.

1. Introduction

The lowland peatlands of south-east Asia represent the largest peatland area in the tropical belt. These peatlands cover approximately 350 000 km^2 and store more than 65 Gt (1 Gt = 10^9 t) carbon, which corresponds to 9% of the global peatland area and 14% of the global peat carbon stock (Joosten, 2009). This major terrestrial carbon reservoir is currently threatened by fire and drainage related degradation and destruction (Miettinen and Liew, 2010). The annual carbon loss from peat fires and oxidation averages more than 220 Mt C (1 Mt = 10^6 t; Couwenberg et al., 2010). In future, south-east Asian peatlands may become an even more significant source of atmospheric carbon when dry-season rainfall decreases as predicted by climate models (Li et al., 2007). Insights into the response of peatlands to climate change can be gleaned from the palaeo-record (Moore et al., 1998; Belyea and Malmer, 2004; Yu et al., 2009). However, a comprehensive synthesis on the timing and pattern of peatland formation and peat accumulation in response to external drivers is lacking for south-east Asian peatlands. The potential role of this important peatland region in the global carbon cycle is often extrapolated from one single core (Page et al., 2004; Rieley et al., 2008).

The largest tracts of south-east Asian peatlands occur on coastal plains and river deltas of Peninsular Malaysia and the islands of Sumatra, Borneo and New Guinea (Polak, 1975; Anderson, 1983). These peatlands are generally convex in shape and ombrogenous, analogous to raised bogs of the Northern Hemisphere (Polak, 1933; Dommain et al., 2010). Ash content and pH are generally low (Neuzil et al., 1993). The natural vegetation of these peat domes is 'peat swamp forest' (Anderson, 1983). Similar peat domes are found in a few inland areas of lowland Borneo, such as the Kahayan –

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Katingan watershed area, the Kutai basin and the Upper Kapuas River basin.

In this paper we synthesise radiocarbon chronologies of lowland ombrogenous peat domes from Peninsular Malaysia, Sumatra and Borneo (Fig. 1). Our aim is to elucidate peat dome initiation and peat accumulation rates in the context of palaeoclimate and post-glacial sea-level changes. Particular emphasis is placed on identifying regional differences in relation to physiographic setting and climate. Peat degradation patterns are examined in light of natural and anthropogenic forces. Finally, we compare carbon sequestration rates of south-east Asian peat domes with raised bogs from the Northern Hemisphere.

2. Regional setting

The study areas (Peninsular Malaysia, Sumatra and Borneo) are connected by the shallow continental Sunda Shelf (Fig. 1). When sea-level was lower and the Sunda Shelf was exposed during the Last Glacial Maximum (LGM) the islands of the western Malay Archipelago were connected to mainland Asia (Molengraaff, 1921). The inner part of this so called "Sundaland" is a tectonically stable area (Tjia, 1996).

Erosion of the central crystalline highlands and subsequent sedimentation has led to the formation of extensive alluvial plains on the coasts of Peninsular Malaysia, eastern Sumatra and north-western and southern Borneo (Brünig, 1974; Verstappen, 1975). Coastal peat domes largely developed on interfluves in these alluvial settings. In southern Borneo lowland areas farther inland are occupied by large Pleistocene podzol terraces (Sieffermann et al., 1987) that below 35 m a.s.l. are partly covered by peat domes (Sieffermann, 1990).

The climate of the study area is controlled by the Asian-Australian monsoon, seasonal shifts of the Intertropical Convergence Zone (ITCZ) and by atmospheric convection from ocean waters of the surrounding Indo Pacific Warm Pool (IPWP). Maritime south-east Asia has a warm and wet equatorial climate with mean monthly temperatures constant between 26 to 27 °C throughout the year. The mean annual rainfall ranges from ~2000 mm (Peninsular Malaysia, south-eastern Borneo) to ~4000 mm (north-western Borneo) (Walter and Lieth, 1960–1967). From November to April the wet northwest-Monsoon brings heavy rainfall to the region. In southern Sumatra and southern Borneo this time marks the wet-season with the annual precipitation maximum occurring in January. The dry southeast-monsoon prevails from May to September. It causes a distinct dry-season in southern Sumatra and southern Borneo with mean monthly rainfall below 100 mm in August. Peninsular Malaysia and the northern parts of Sumatra and Borneo are under strong influence of the ITCZ throughout the year and lack a clear dry season (Aldrian and Susanto, 2003).

Interannual variation in rainfall is strongly correlated to the El Niño-Southern Oscillation (ENSO; Hendon, 2003). El Niño events are associated with more pronounced and extended droughts. La Niña events are associated with anomalously wet conditions. In recent decades, large scale fires during El Niño related droughts severely affected forests and peatlands in the region (e.g. Siegert et al., 2001; Goldammer, 2007).

Peninsular Malaysia, Sumatra and Borneo all belong to the same biogeographic region of Sundaland and display close floristic similarities (Whitmore, 1975).

3. Material and methods

Radiocarbon dates from domed peatlands on Peninsular Malaysia, Sumatra and Borneo (5° N - 3° S and 116° - 102° E) were collected from published and other sources. Based on available data, we distinguish three types of domed peatlands, (i) peatlands in coastal

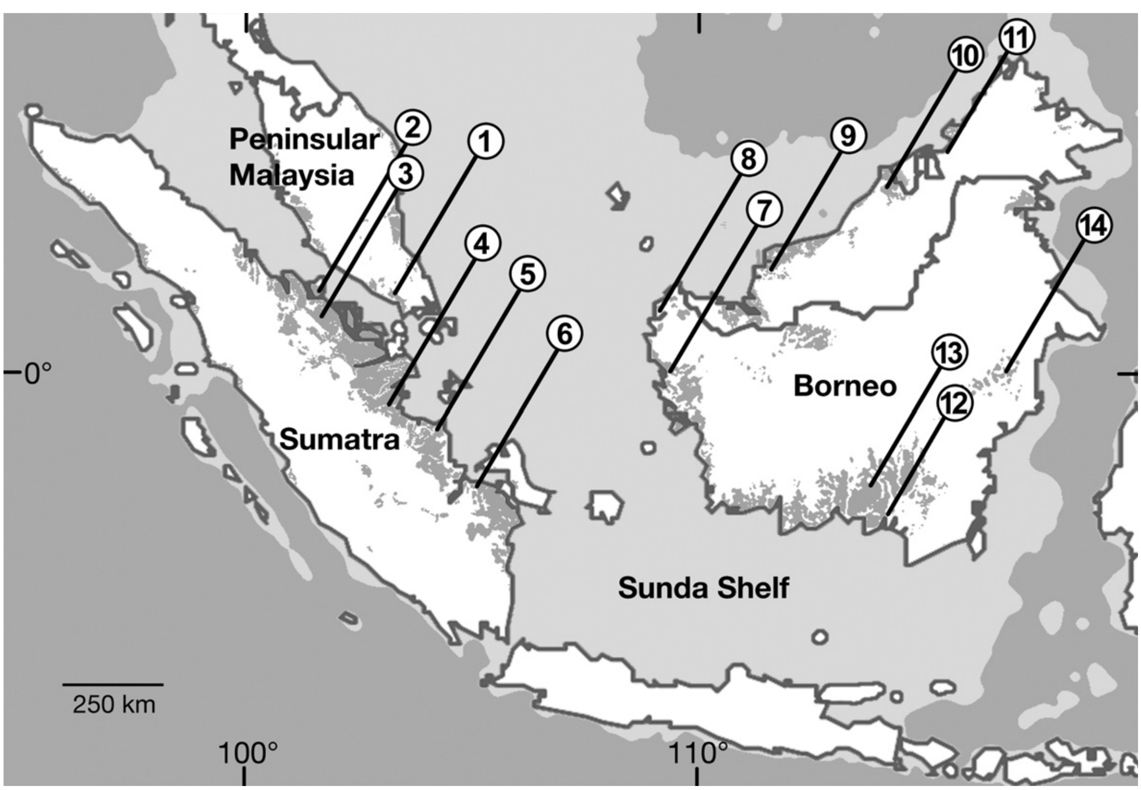

Fig. 1. Map of the western Malay Archipelago with the approximate position of the study sites listed in Table 1. Dark shaded areas denote occurrence of lowland peat soils (based on Staub and Gastaldo, 2003; Wahyunto et al., 2003, 2004; Wetlands International, 2010). The light shaded area delineates the Sunda Shelf as it was exposed at the time of the Last Glacial Maximum (based on Sathuamurthy and Voris, 2006).