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Invited review

Carbon storage and release in Indonesian peatlands since the last deglaciation

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A B S T R A C T

Peatlands have been recognised as globally important carbon sinks over long timescales that produced a global, net-climatic cooling effect over the Holocene. However, little is known about the role of tropical peatlands in the global carbon cycle. We therefore determine the past rates of carbon storage and release in the Indonesian peatlands of Kalimantan and Sumatra – the largest global concentration of tropical peatlands – since 20 ka (kiloannum before present). Using a novel GIS (geographic information system) approach we provide a spatially-explicit reconstruction of peatland expansion in a series of paleogeographic maps.

Sea-level change is identified as the principal driver for peatland formation and expansion in western Indonesia as it controls both atmospheric moisture supply and the hydrological gradient on the islands. Initiation of inland peatlands in Kalimantan was coupled to periods of rapid deglacial sea-level rise with rates of over 10 mm yr^{-1} whereas coastal peatlands could only form after 7 ka when the rate of sea-level rise had slowed to 2.4 mm yr^{-1}. Falling sea levels after 5 ka led to rapid peatland expansion in coastal lowlands and a doubling of the total peatland area in western Indonesia to 131,500 km^2 between 2.3 ka and 0 ka. As a result of slow peatland expansion from 15 to 6 ka and rapid expansion afterwards the rate of annual carbon storage of all western Indonesian peatlands remained <1 Tg C yr^{-1} until 6 ka and then increased to 7.2 Tg C yr^{-1} by 0 ka. Associated with this rise in carbon storage was an exponential growth of the peat carbon pool from 0.01 Pg C by 15 ka to 23.2 Pg C at present, of which 70% is stored in coastal peatlands. In inland Kalimantan peatlands, falling sea levels together with increased El Niño activity induced an annual carbon release of 0.15 Tg C yr^{-1} from aerobic peat decay since 2 ka. Cumulative carbon losses from anaerobic decomposition do not seem to limit peat bog growth in the tropical peatlands of Indonesia. Carbon losses from Holocene peat fires are only known from the Kutai basin since 4.4 ka with an associated release of 0.1–3.6 Tg C per fire event, which never surpassed the contemporaneous annual C storage. The peatlands of western Indonesia were thus a persistent carbon sink since 15 ka but this sink was of global importance only over the past 2000 years when it likely contributed to a slower growth in atmospheric CO_2 concentrations. Currently, annual losses of carbon from peat drainage and fires are on average 28 times higher than the pre-disturbance rate of uptake implying that this carbon reservoir has recently switched from being a net carbon sink to a significant source of atmospheric carbon and is currently in danger of eradication.

1. Introduction

Tropical peatlands are an integral part of the Earth's terrestrial biosphere and have been an important component of the global carbon cycle since the Middle Paleozoic as indicated by continental coal deposits (Berner, 2003; Greb et al., 2006). Coal reservoirs are generally derived from peat deposits produced by swamp forests, in which woody material only partially decomposes in a waterlogged setting (Hedges et al., 1985). The equatorial peatlands of Indonesia, Malaysia, and Brunei (Southeast Asia, Fig. 1) are generally considered to represent important modern analogues for past coal forming environments (Cobb and Cecil, 1993).

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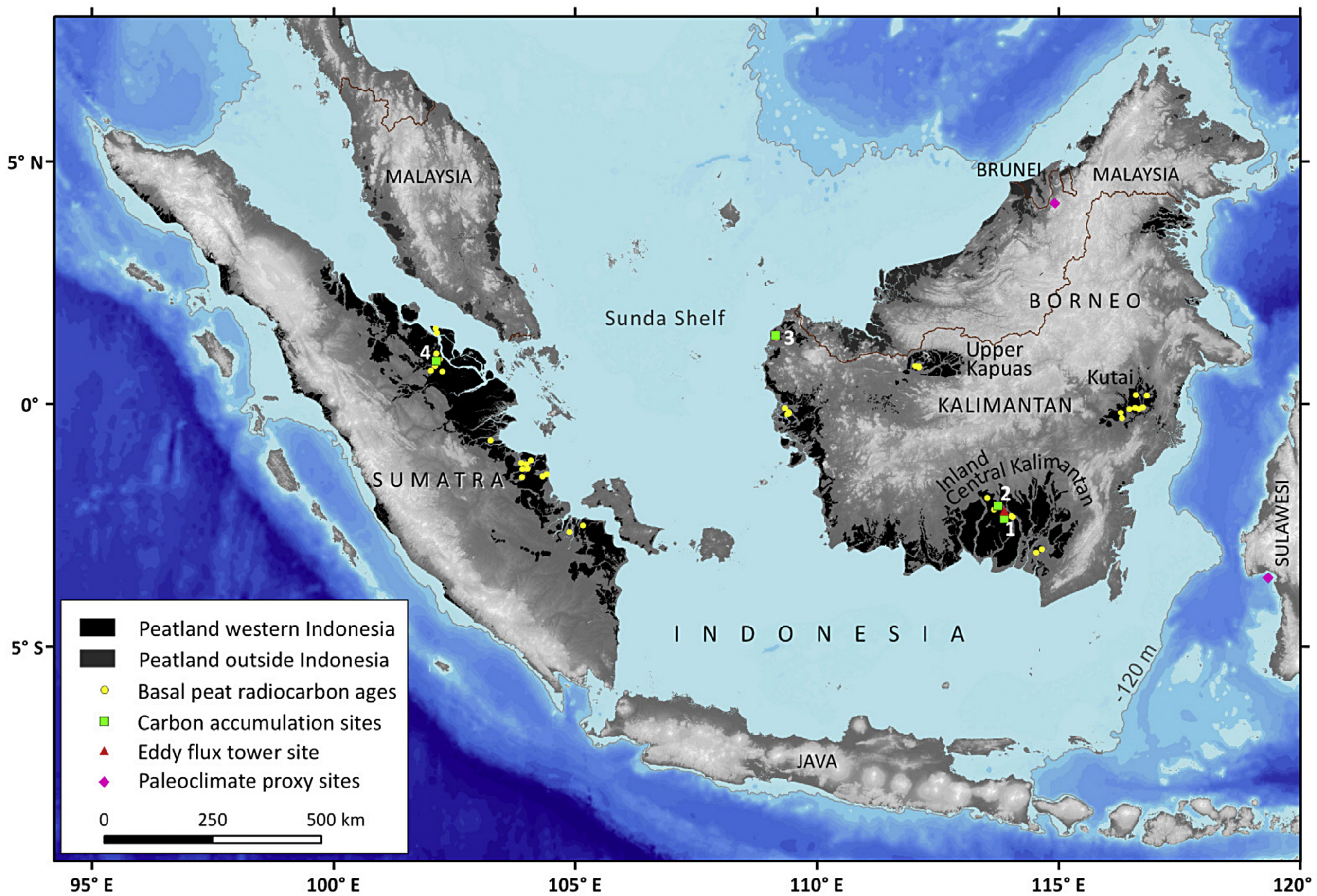

Fig. 1. Peatland distribution in the Sunda-region. Black areas represent the lowland peatlands of western Indonesia, dark grey areas peatlands in Malaysia, Brunei and Thailand. Locations of basal peat dates are marked by yellow dots. Locations of carbon accumulation records from western Indonesia are marked by green squares and numbered: 1) Sebangau, 2) Palangka Raya, 3) Teluk Keramat, 4) Siak Kanan. The eddy flux tower site of Hirano et al. (2007, 2012) is marked by a red triangle and the paleoclimate proxy sites of Partin et al. (2007) in northern Borneo and Tierney et al. (2012) off Sulawesi by pink diamonds.

Peatlands are known from equatorial Southeast Asia since the Paleocene, with the first ombrotrophic peat formations developing in the Late Oligocene (Morley, 2012, 2013). Domed peatlands were widespread in the Miocene and pollen records of their coal deposits reflect floristic assemblages strikingly similar to modern peat swamps of Southeast Asia (Anderson and Muller, 1975; Moore and Hilbert, 1992; Demchuk and Moore, 1993; Morley, 2012, 2013). Modern peat swamp forests are thus an ancient ecosystem that has been an element of Southeast Asia's vegetation for 15–20 million years (Morley, 2012, 2013). During the Cenozoic, Southeast Asian peat swamp forests have effectively transferred carbon from the atmosphere into terrestrial peat deposits, which in certain tectonic settings were eventually buried and preserved within the geologic rock reservoir. The modern peatlands of Indonesia therefore provide a unique, but rapidly disappearing opportunity to study the influence of peat swamp forests, as analogues of ancient coal forming ecosystems, on the global carbon cycle over millennial timescales.

Approximately half of all known tropical peatlands and 84% of those in Southeast Asia are located in Indonesia (Page et al., 2011). Indonesian peatlands are relatively young geologic deposits that mostly originated during the past 14,000 years (Dommain et al., 2011), but spatially and temporally explicit information on their origin and development is rare. Currently, estimates are only available for 1) the current carbon pool that is stored in Indonesian peatlands, 2) the age of initiation for selected peatlands and 3) the past rates of peat accumulation for an even more limited number of sites. A more detailed spatial and chronological context to these estimates is needed to understand how the carbon fluxes and the build-up of the carbon pool in Indonesian peatlands were affected by changes in sea level, climate, and paleo-drainage networks.

Sea level has been invoked as an important driver for the formation of Southeast Asian peatlands during the Cenozoic (Dommain et al., 2011; Morley, 2012). Dommain et al. (2011) suggested that both the rise and subsequent fall in sea level during the Holocene induced peatland initiation across western Indonesia, Malaysia, and Brunei. Moreover, sea-level changes over the Sunda Shelf seem to be particularly important in regulating the regional moisture availability on glacial–interglacial timescales (DiNezio and Tierney, 2013). However, a more quantitative approach is needed to determine the influence of sea-level changes on the spatial expansion of peatlands in Indonesia and to identify potential thresholds that trigger their initiation.

The carbon balance of tropical peatlands also seems to be strongly influenced by rainfall seasonality, including variability in the El Niño-Southern Oscillation (ENSO), as shown by modern carbon flux studies (Hirano et al., 2007, 2012). However, no general understanding exists on how rainfall and other climate factors influenced the long-term carbon balance of tropical peatlands. Because Indonesian peatlands are generally dome-shaped landforms that solely rely on atmospheric sources of water (Dommain et al., 2010) their peat layers should preserve a sensitive record of the carbon cycling responses to past climatic changes.