**LETTER**

The oldest extant tropical peatland in the world: a major carbon reservoir for at least 47,000 years

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Abstract

Tropical peatlands in Southeast Asia cover ~25 million hectares and exert a strong influence on the global carbon cycle. Recent widespread peatland subsidence and carbon dioxide emissions in response to human activity and climate change have been well documented, but peatland genesis remains poorly understood. Unlike coastal peatlands that established following sea-level stabilization during the mid-Holocene, inland peatlands of Borneo are little studied and have no apparent environmental constraint on their formation. Here, we report radiocarbon dates from the Upper Kapuas Basin which show inland peat formation since at least 47.8 thousand calibrated radiocarbon years before present, ka. We provide a synthesis of new and existing peat basal dates across Borneo, which shows a hiatus in peat genesis during a cool and dry period from 30 to 20 ka. Despite likely peat degradation during that period, the Upper Kapuas is still exceptionally deep, reaching a maximum depth (determined from coring) of 18 m. Our best estimate of mean peat depth over 3833 km$^2$ of the Upper Kapuas is 5.16 ± 2.66 m, corresponding to a carbon density of 2790 ± 1440 Mg C ha$^{-1}$. This is one of the most carbon-dense ecosystems in the world. It withstood the glacial-interglacial climate transition and remains mostly intact, but is increasingly threatened by land-use change.

1. Introduction

Tropical peatlands in Indonesia have become a large source of carbon emissions due to land clearance, drainage and disastrous forest fires over the past three decades. For example, the El Niño related fire event in 1997 released up to 2.6 Gt C (Page et al. 2002, Lohman et al. 2007), roughly equal to half of current US annual carbon emissions, and subsequent anthropogenic fires occur consistently during the dry season and peaking during El Niño periods (Cattau et al. 2016). From 2000 to 2010 alone, around 2.7 million ha of peatlands in Indonesia were deforested and degraded (Miettinen et al. 2011). However, over at least the past several thousand years, tropical peatlands have functioned as a carbon sink, currently storing more than 104.7 Gt carbon (Dargie et al. 2017). The history of peatland formation, and fundamental properties of their extent, depth, and age remain poorly constrained for large parts of Southeast Asia. For example, improvements in mapping methods have shown original studies underestimated peatland extent and depth (Osaki and Tsuji 2016). In addition, little is known of the ages of tropical peatland initiation, which constrains the peat carbon stock and provides crucial information regarding the past climates suitable for peat growth (Treat et al. 2019).

Despite their importance on a global scale, tropical peatlands are much less studied compared to their temperate and boreal counterparts (Yu 2012, Osaki and Tsuji 2016). Globally, out of 3983 dated peatland sites, only 198 are from the tropics, and only 80 of those are in Southeast Asia, despite the fact that this area contains the deepest and most spatially continuous peat areas in the tropics (Gumbricht et al. 2017, Treat et al. 2017). Tropical peatlands in Southeast Asia can be divided into coastal peatland, which established after ca. 8 ka (thousand calibrated radiocarbon years before present) when sea level decreased and
stabilized, and inland peatland which formed much earlier during the Late Pleistocene (Dommain et al 2011). The peatlands in this area initiate within broad inundated basins, eventually accumulating sufficient organic matter to form raised dome structures that support tropical forests (Anderson 1963). Peatlands usually form and accumulate faster during the warm and wet climates of the interglacial period (Fischer et al 2018). While temperate peatlands were overrun and degraded by ice sheets during glacial periods, tropical peat may have remained intact, despite possible degradation due to a colder and drier climate (Treat et al 2019). In this study, we highlight the differences of formation times and depth profiles between coastal and inland peatlands, and how the climate possibly affected peat formation. As there is not yet any estimate of the carbon stored in the inland peat of West Borneo, we provide the first estimation of the timing of peat genesis and carbon accumulated since then.

2. Materials and methods

2.1. Study area

Sampling sites are located in West Kalimantan, a province of Indonesia with approximately 1.7 million ha of peat (Ritung and Subagjo 2004, Ritung et al 2011). This province contains the Kapuas River—the longest river in Indonesia—which defines two distinct peatland regions, inland peatland in a large upstream basin and floodplain, and coastal peatland on the river deltas. We expect these two regions will have distinct characteristics, because based on their elevation, the upstream region always remained above sea level during the Quaternary, meanwhile the coastal region was affected by sea level changes and delta formation (Dommain et al 2014).

We laid two main transects across two peat domes, Rasau Jaya in the Kapuas delta region, and a dome south of Putussibau in the Upper Kapuas Basin region (figure 1). In addition to these two transects, we also collected several cores from three other areas (Ketapang, Gunung Palung and Sentarum). The samples from Sentarum were collected in 2011, while the other samples were collected during 2017–2019. Among these sites, Sentarum and Gunung Palung are protected within national parks, while other locations were disturbed by burning, clear cutting and replaced by abandoned forest or plantation.

2.2. Sampling method

We collected peat cores using Russian peat corers. We used a 52 mm diameter Russian peat corer to obtain samples down to the mineral layer. At the main transects in Rasau Jaya (Kapuas delta) and Putussibau (Upper Kapuas), we collected two sets of cores spaced at ca. 1 km. One core was used for carbon and bulk density analysis and one core for other peat properties. For the first core, in each 25 cm segment we subsampled 10 cm for bulk density and loss-on-ignition analysis. For the second core, in 5 cm contiguous samples, we sampled 20 cm from the center of the core, so the outer part of the core does not contaminate the sample. We stored the samples in sterile bags and kept them at 4 °C except during transport. In between the main sampling sites we took an additional core for the only purpose of measuring the peat depth and therefore did not take samples.

We had technical difficulty in cores P3, P4, and P5, where we were unable to collect samples to the

Figure 1. Sampling location map with detailed coring site on the subsets. Two main transects located in Putussibau (inland peat) and Rasau Jaya (coastal peat). Other sites are sampled randomly.
bottom of the peat as we repeatedly encountered a layer of buried hardwood at ca. 10–11 m depth. This hardwood layer twisted and opened the corer when we tried to collect samples from this depth. The layer was encountered in at least 10 locations over a ca. 30 m² area around sampling points. Therefore, in these cases we changed the objective to obtaining samples as deep as possible rather than contiguously through the woody layer (See figure 3). In core P3, we were able to collect a 5 cm segment sample from the bottom of the peat at the depth of 15 m. However, at core P4 and P5, we did not reach the mineral layer at the depth of 15 m, which is the maximum depth reached by our corer. Therefore, we assume that the bottom of the peat is topographically flat with the adjacent site (P3.5), resulting in estimated depths at P4 of 17 m and at P5 of 16.9 m. This estimate is also supported by one of the author’s (G.Z.A.) ongoing coring project who found a peat depth of 18 m roughly 1 km west of our transect (RSS GmbH 2018).

2.3. Radiocarbon dating
We used 5 cm segment samples for radiocarbon dating the base of the peat cores. We sieved 1 cc bulk peat to obtain the 125–500 µm fraction, which was then treated with HCl and KOH rinses. For some samples (RC cores from Ketapang), we also picked out larger material (>500 µm) to date. We sent 25 samples to the NOSAMS Woods Hole facility and seven samples (from Sentarum sites) to Waikato in New Zealand (See table S1 (available online at https://stacks.iop.org/ERL/15/114027/mmedia) for the details). We calibrated the dates following IntCal13 (Reimer et al. 2013).

Various materials may produce different ages due to peat layer dynamics. For example, pollen and macrofossil material have yielded consistent ages because they tend to stay at the same layer, however the bulk peat material might date younger than the actual age due to root intrusion (Wüst et al. 2008). To test the effect of material type on radiocarbon ages, we dated two types of material from the RC cores. In our comparisons from two cores (RC1 and RC3), there were insignificant differences (<100 years) between ages derived from bulk material and plant macrofossils (>500 µm). In a third core (RC2), we found that the woody material was 1200 years older than the bulk peat. As these results disagree with Wüst et al (2018), we decided to date only woody material sieved from bulk peat (125–500 µm) for the core transects.

2.4. Elevation measurement and peat profile
We used RTK (real-time kinematic) GPS to measure the elevation of the transect points across the peat domes in Rasau Jaya and Putussibau. At each site, we collected multiple sessions of 20 to 60 min of raw GPS data as RINEX (receiver independent exchange format) files using RTK-Lib software with data from Continuously Operating Reference Stations in Putussibau and Pontianak and atmospheric correction data from Global Navigation Satellite Systems (GNSSs). We retained only observations with high positional accuracy rated as Q1 and Q2 in RTK-Lib. Using the Earth Gravitational Model 2008 (EGM2008), we adjusted the ellipsoid elevation to elevation above mean sea level.

2.5. Carbon stock estimation
We estimated the total carbon stock of peats in the Upper Kapuas Basin following equations by Yu (2012) and Lawson et al. (2015), where the carbon stock is calculated from area, depth, bulk density and carbon content (See supplementary 1 for detailed calculation). As there is uncertainty of the total peat coverage in this region, we estimated the carbon stock from two maps of peat area: Global Forest Watch (2461.32 km²) and Badan Restorasi Gambut (BRG, Peat Restoration Agency) of the Indonesian Government (3833.2 km²; figure S2). For the average depth of the peat, we used two values. One is the average depth of our 14 sampling points, and the other is the estimated depth from a simple relationship between peat depth and distance to the peat edge (estimated from the transect cores) and extrapolated to all peatlands in the upper Kapuas. The bulk density value is directly from the measurement of 10 cm subsamples every 25 cm of the core. Sample volume was measured using water displacement of tightly wrapped samples. To obtain the carbon content, we used the LOI (loss on ignition) of the bulk-density samples (normally >95%) and published values for percent total organic carbon of peat at similar sites (Agus et al. 2010, Anshari et al. 2010) to estimate the carbon density and finally carbon concentration. As we have two values of area and two values of depth, we calculated four estimates of the carbon stock.

3. Results

3.1. Peat basal radiocarbon dates
We obtained 37 radiocarbon dates from five sites, of which 26 are basal dates (table S.1). The oldest calibrated age from each site ranges from 4.5 ka to 47.8 ka (figure 2). Overall, we found a weak correlation between age and depth of the peat (See table S.2.2). Basal radiocarbon dates at Rasau Jaya show similar ages across the transect, while basal radiocarbon dates at Putussibau show that ages tend to be older at the center of the dome. We also observed that the inland peat is much deeper compared to coastal peat (figure 3).

At Rasau Jaya, five basal radiocarbon dates from cores with depths of 0.6 to 5 m show ages of 4.0–4.5 ka. We found a negative correlation between depth and basal age in this area, due to the deepest core R3 is located in very degraded peat, and only
60 cm peat remains. At Putussibau, we obtained five dates between 18 and 48 ka, with an upper estimation of >50 ka for the oldest date (See table S.1, core ID P4).

At Sentarum, the oldest date is from a shallow peat (19.8 ka at 2 m depth), while the deepest peat (14 m) is only aged 13.5 ka. A previous study in this area shows a date of 45.6 ka at a depth of only 0.8 m (Anshari et al 2004). At Gunung Palung, despite its closeness to the coastline (12 km), we found a quite old age (9.3 ka), indicating that this site is categorized as inland peatland. However, the peat is extremely shallow for an inland peat (e.g. TZII at 0.9 m, 8.1 ka and TZIII at 1.3 m, 9.3 ka). The Ketapang site is located further inland than Gunung Palung (45 km from coastline) and has a depth of 8.5 m and an age of 10.9 ka.

3.2. Carbon stock estimation
We estimated the carbon stock in the Upper Kapuas basin region based on our Putussibau transect depth, because the great depth and age found in our cores suggest this region is a potentially a large and long-term carbon store. Of the four estimates from different peat extent and mean depths, our lowest estimate is 0.78 ± 0.47 Gt C while our highest estimate is 2.14 ± 0.62 Gt C (table 1). The large range resulted from the 55% larger extent of the BRG map and the difference in average depths estimated directly from the sampling sites (10.35 m) or estimated from a depth model (~5.5 m). We also estimated the carbon density per area by dividing the carbon stock by total area. If using the more recent BRG map and the potentially more accurate modelled depth estimates, the estimate for carbon density is 2790 ± 1440 Mg C ha⁻¹.

4. Discussion
4.1. Peat depth and age at coastal and inland sites
Most of the 25 million hectares of tropical peatlands in Southeast Asia have been deforested and/or drained, leading to widespread subsidence and carbon dioxide emissions (Hoyt et al 2020). Understanding when and how peatland formed in this region is therefore crucial for prevention and reversal of subsidence and carbon loss going forward. West Kalimantan (Borneo) contains 1.7 million ha of mapped peatlands, and approximately 39% is inland peatland (based on the map from BRG). However, only three radiocarbon-dated peat cores have been previously published: in the Sentarum Lake system dating to 45.6 ka (thousands of years, calibrated, before present) (Anshari et al 2004), at Rasau Jaya dating to 4.1 ka (Anshari et al 2010) and at Teluk

Figure 2. Oldest peat basal radiocarbon date from each site. Boxes show the oldest median calibrated age and the corresponding peat depth found at each location. Teluk Keramat and Rasau Jaya are coastal peatlands near sea level. *Blue dates are from previous studies at Rasau Jaya (Anshari et al 2010), Sentarum (Anshari et al 2001) and Teluk Keramat (Neuzil 1995).
Table 1. Estimate of carbon stock and carbon density in upper Kapuas basin based on two different map (global forest watch and badan restorasi gambut) and different depths (average sampling site and modelled).

| Area and depth value sources          | Total carbon stock (Gt) ± 95% CI | Carbon stock per area (Mg C ha⁻¹) ± 95% CI |
|---------------------------------------|-----------------------------------|------------------------------------------|
| GFW map, sampling-sites depth         | 1.37 ± 0.40                       | 5590 ± 1610                              |
| BRG map, sampling-sites depth         | 2.14 ± 0.62                       | 3180 ± 1910                              |
| GFW, modelled depth                   | 0.78 ± 0.47                       | 2790 ± 1440                              |
| BRG, modelled depth                   | 1.07 ± 0.55                       | 3180 ± 1910                              |

Figure 3. Dome profiles from (A) coastal peat and (B) inland peat. (C) Scaled comparison at the bottom with a 170 cm human for scale. Four sampling points (P4, P4.5, P5 and P5.5) at Putussibau did not reach the basal mineral layer, as shown by the black line. Elevation is the altitude above the mean sea level and distance is the position of cores along the transect. Detailed transect maps are available in figure S1. Blue bars show river levels and flood stages (unknown for Manday River), and the tidal range at Rasau Jaya.

Keramat dating to 4.5 ka (Neuzil 1995). Thus, 32 radiocarbon dates from this study help to provide a better picture about the age of the peatlands in this region.

We found that coastal and inland peat domes may achieve thicknesses of 4–6 m and >17 m, respectively, confirming earlier studies (Anderson 1963, Cameron et al 1989, Page et al 2011). While peat age may explain the large differences in peat thickness, we should also consider the human impact on peat depth. Shallower depths (<1 m) at the southern six km of the Rasau Jaya transect indicate a major disturbance that caused peat loss. This area was extensively cultivated and burned following development for agricultural by the Indonesian government transmigration program in the 1970s. Only 20%–30% organic content remain in this area (and technically are no longer categorized as peat) compared to >90% organic content in the relatively intact dome center at 4–6 m depth. In contrast, Putussibau was only partially disturbed since the 1990s, with 2–4 m peat depth at the edge and approximately 17–18 m at the center.

The ages of the domes are also extremely different. The coastal Rasau Jaya basal dates are all approximately 4 ka, similar to the Teluk Keramat coastal peat (figure 2), indicating simultaneous formation of the peatlands. This is consistent with late Holocene sea level decline that resulted in replacement of mangrove by forested peatlands, a processes underlying most Bornean and Sumatran coastal peats (Dommain et al 2014, Fujimoto et al 2019). Here, high tide often reaches 1.35 m (Kastner et al 2017). Thus, during the highest tides the degraded portions of this peat are inundated or saturated with brackish water, possibly reducing the agricultural value of this land. This tidal influence and salt water intrusion are exacerbated by anthropological peat drainage and sea level rise, and possibly develops a high energy environment that halts future peat accumulation (Whittle and Gallego-Sala 2016). This peat loss resulted in a negative correlation between peat depth and age at Rasau Jaya (table S2.2). The Gunung Palung site, despite its thin peat and its proximity to the coast, is categorized as inland peat as it is much older (9.3 ka) than the sea level rise of the mid-Holocene. However, it is much thinner compared to the nearby inland peat in Ketapang, suggesting historical peat loss within this national park.

In contrast to the coastal peatlands, the inland Putussibau dome has basal ages ranging from 18 to 48 ka. It is possible that modern carbon was added into the deeper peat through root exudates and rhizodeposition, microbial biomass decomposition and leaching of dissolved organic carbon, all of which interact throughout the profile (Silva and Lambers 2020) decreasing the radiocarbon ages (Balesdent et al 2018). However, we dated woody fragments >125 microns that were treated with several KOH measurements, and we found no large or consistent difference between dates of different size fractions.
Thus, we regard these dates as the best possible estimate of peat initiation (supplementary table S2), even though soil organic matter is expected to be older than living plants at any given point in time (Silva 2017). The oldest date at Putussibau calibrated to the limit of the Intcal13 calibration curve, at least ca 48 ka ago, with maximum limit at >50 ka: the date was statistically different from concurrently-run organic carbon blanks and therefore remains constrained within the radiocarbon time scale. This date places the inland peatland in Putussibau as the oldest intact and active peatland (Treat et al 2017). This oldest dated sample comes from the depth of 15 m, while we predict that the peat in Upper Kapuas Basin could reach 17–18 m. Thus, a better method than hand-operated peat corers is required to obtain samples and date carbon deposited at the base of the peat.

Regardless of methodological limitations, the basal radiocarbon dates reported here show that the age of deposition was older at the center of the dome, which indicates that the peat started to form from a point of depression at the center, possibly an oxbow lake, that became terrestrialized by the peat and then expanded laterally (Foster and Wright Jr, 1990, Belyea and Baird 2006). We also noticed that the base of the peat is approximately 5 m below the Kapuas river bed, which could indicate river-bed aggradation and water-table rise since the glacial period. This increasing water table probably released the hydrological limitation of peat upward growth (Ingram 1982, Belyea and Baird 2006), thus enabling the peat to grow up to 17–18 m depth. Half of the Putussibau dome lies below the river level, indicating its importance as a hydrological buffer, where the wetland system in the Upper Kapuas Basin stores approximately 20% of the volume of the water in the Kapuas River and its floodplain lakes (Law et al 2015). Recent land-use change and peat degradation near Putussibau is possibly linked with the increasing frequency of flooding events (Wells et al 2016).

At the Sentarum site, negative correlation between depth and age (Kendall’s $\tau = -0.833$) suggests that peat formation and growth are very heterogeneous across space and time in this area. The discrepancies between age and depth implies a dynamic in peat dome growth and degradation even in the absence of human causes, where old peat stopped accumulating or even degraded as new domes formed elsewhere. A possible cause for this heterogeneity is the adjacent large seasonal lake system where local peat initiation may be linked to the spatial and temporal heterogeneity of water levels within this large lake system (Hidayat et al 2017).

### 4.2. Climate history and peat formation

Coastal and inland peat formation in Southeast Asia region react differently to climate (Dommann et al 2011). Coastal peat mainly formed at the earliest after sea level stabilization ca. 8 ka (Dommann et al 2011, Treat et al 2019), while our results shows that inland peat possibly started to form much earlier at >50 ka. To explain the potential effects of climate on peat formation, we combined our data with other 37 radiocarbon dates available from Borneo (See table S.1). We aligned our basal dates with the geographically closest climate record from cave stalagmites in Gunung Buda located 460 km to the NE of our Putussibau site (figure 4; Carolin et al 2016).

Based on the comparison between peatlands initiation time and the climate, we observe an inland peat-formation hiatus around 20–30 ka, generally aligned with the glacial maximum (Clark et al 2009). Moreover, as in other tropical regions, higher $\delta^{18}$O ratios in the cave carbonate record (ca 25–17 ka) indicates lower precipitation and a colder climate (Ward et al 2019), a signal that was likely preserved in peat $\delta^{18}$O ratios, such as cellulose and lipids (Maxwell et al 2018), which should be considered in future paleo climatic reconstructions. A sea-surface temperature reconstruction also shows cooler temperatures and a warm-up shortly after 20 ka (Mohtadi et al 2010). These records are also consistent with a cooler Northern Hemisphere, which shifted the Inter Tropical Convergence Zone (ITCZ) southward, creating stronger monsoon precipitation over Australia, and a drier climate over Kalimantan (Denniston et al 2013). A colder and drier climate likely resulted in a hiatus of new peatland initiation and possibly a negative carbon balance (Maxwell and Silva 2020) during a period that overlaps with the peat stratigraphy from South Kalimantan, where the peat accumulation underwent a hiatus from 27–14 ka (Wüst et al 2008). Out of 37 peat basal dates from various studies in Borneo, only one formed during this hiatus period (Page et al 2004). Despite the peat-formation hiatus, the climate during this period seems sufficiently wet to sustain the existing peatlands, which is consistent with a pollen record (Anshari et al 2001) and biogeographic evidence for continuous forest cover through the glacial period (Bird et al 2005, Suraprasit et al 2019).

Around 15–7 ka, we observed a cluster of peat initiation events at Ketapang and Gunung Palung. This peat formation was possibly caused by an increase in precipitation through the early Holocene, when the northern hemisphere warmed and the ITCZ advanced northward, which was coupled with the sea-level rise from deglaciation (Griffiths et al 2013). At a finer temporal resolution, the apparent association of peat initiation at Sentarum and Putussibau with Heinrich Events (abrupt Northern-hemisphere cold intervals during the Pleistocene) suggests an opposite climatic relationship, though how these events are expressed in the local hydroclimate is not understood. After sea level stabilization at 8 ka, we see peat formation initiate at several coastal sites. Our sample in
Rasau, which dates to 4.5 ka, probably formed later after the Kapuas River delta accumulated enough land for peat to grow. However, relative to their young age, the coastal peats are quite deep, indicating that they grow much faster (possibly due to a warmer and wetter climate), a finding consistent with other studies of peat growth rate across Southeast Asia (Page et al 2004, Dommain et al 2014). Future radiocarbon dating across the vertical plane of the core will show further how the climate affected peat growth and dynamics after peat initiation.

4.3. Carbon stock estimation
With our limited data, we predict that the inland peatland in the Upper Kapuas basin contains at least 0.78 ± 0.47 Gt C and a maximum of 2.14 ± 0.62 Gt C
(table 1). The total peat carbon stock of Indonesia is estimated to be at 25.33 Gt C and on Borneo at 9.08 Gt C (Warren et al. 2017). However, the Warren et al. (2017) estimate lumped peat at >3 m as a single depth class. As we observe in the field, and based on our modelling, the depth of inland peatland is often underestimated by prior studies.

Our method that produced the lowest estimate of carbon density (using modelled depth from the BGR map), still shows a mean estimate of 2790 ± 1440 Mg C ha⁻¹. However, this estimate is a subject to a very large degree of uncertainty due to our limited field data. Hopefully, future coring projects in this area combined with more advanced topographic remote sensing will provide a better estimate of the carbon stock in this region. We do not include the above-ground biomass in this value as we did not collect vegetation biomass data since our transects are located on secondary forests which were recently burned and/or deforested. Some areas were already transformed either to abandoned bush fern field or small plantations. A previous study in the Sentarum region shows that the carbon density average at 156 Mg C ha⁻¹ for above ground biomass and 3228 Mg C ha⁻¹ below ground biomass (Anshari et al. 2012). Most of the carbon of this tropical ecosystem is stored in the soil.

Our carbon density estimate shows that the Upper Kapuas Basin is more than twice as deep (and more than twice the C stock) than the average Indonesian peat (Page et al. 2011, Osaka and Tsuji 2016). This also shows that this inland peatland is more C-dense than boreal peats (average 600–700 Mg C ha⁻¹) (Yu 2012) or the most C-dense forested peats in the Amazon (1390 Mg C ha⁻¹) (Draper et al. 2014). Thus, not only have these deep inland peats provided a carbon sink that has persisted from glacial to interglacial climates, they are likely the most carbon-dense ecosystem in the world.

5. Conclusion

In this study, we provide new data that improve our understanding of tropical peatlands initiation and carbon accumulation. Most of the peatlands of Borneo formed <20 ka, however, we found a peat deposit of greater depth (ca. 18 m) and age (>48,000 years) in a large understudied peatland region, suggesting that peatlands older than the glacial maximum are more extensive than previously estimated (Treat et al. 2019). Our findings point to a new possibility to use these old and deep peat deposits as a long-term environmental archive. We also note that not all old peats are deep. Some shallow peats, 1–2 m in depth, had an old age (>10 ka). Typically, peat of this age is at least 5 m thick, thus indicating extreme peat loss and/or subsidence. Additional radiocarbon dates at the top of cores could reveal the timing and the cause of disturbances to this peat. Finally, our results highlight the importance of inland peatlands for conservation and climate change mitigation. Due to their exceptionally high carbon density, disturbance on this ecosystem can release a large amount of stored carbon. For our site, we estimate that for each hectare of peat that is lost ~2800 Mg C could be released to the atmosphere. While only 7% of the inland peat in West Kalimantan has been logged and converted to plantations to date (Miettinen et al. 2011), 76% occurs outside protected areas (figure S4). Despite their small extent, the deep inland peats of Kalimantan are a long-term carbon reservoir and hydrological buffer that requires immediate conservation and restoration.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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Author contributions

All authors conceptualized the study, devised the methodology and conducted the field investigation. D G G, G Z A and L C R S supervised and provided resources. D G G & M R acquired the funding. M R curated, analyzed and visualized the data. M R wrote the original draft, all authors discussed the results and contributed to the final manuscript.

Competing interests

Authors declare no competing interests.
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