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Land use, hydroclimate and damming influence organic carbon sedimentation in a flood pulse wetland, Malaysia

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ABSTRACT: Water bodies located in floodplains and tropical forests are known to be important carbon stores, but many are subjected to intensive pressures from damming, land use and climate changes. Sedimentary records preserve long-term archives for understanding how such changes affect the quantity and quality of carbon stores. We analysed sediment cores from seven sites across a flood-pulse multi-basin wetland, Tasik Chini in Peninsular Malaysia (for percentage LOI_{550}, sediment density and spheroidal carbonaceous particles), and conducted more analyses on three ^{210}Pb-dated cores (X-ray fluorescence of elements, grain size analysis, carbon isotopes, C/N ratios, carotenoid pigments) to gain an understanding of the drivers of organic carbon accumulation rates (OCARs) since 1860 CE. The median OCAR of 85 g m^{-2} a^{-1} for the basin since 1945 CE was higher than in other floodplain and temperate lakes and in line with other tropical forest lakes. However, we found evidence for different mechanisms of OC deposition across the basin. In 'autochthonous mode', the site with minimal local land disturbance had lowest OCARs and OC was derived mainly from autochthonous production, which rose slightly around 1940 CE when regional land disturbance increased nutrient influx to the basin. The site with the most long-term and intensive land disturbance through forest removal (1940s) and then conversion to rubber and oil palm farming (1980s) functioned mainly in 'allochthonous mode'; that is, increases in OCARs after 1940 CE were driven by deposition of soil-derived OC. The highest OCARs were in the basin that was converted to oil palm after the 1980s and had increased iron mining activity in the 2000s; because this site was located distal from the flood pulse and became increasingly hydrologically disconnected after a low rainfall period in the 1970s, the lake responded strongly in 'autochthonous mode', through encroachment of fringing swamp, the spread of benthic algae and macrophytes, and efficient sediment retention. Weir installation in 1995 CE raised water levels and increased lentic conditions, promoting autochthonous OC production and sedimentation across all basins. The long-term fate of this more recently deposited OC remains uncertain because it is more labile. Overall Tasik Chini has responded strongly to land use changes since at least the 1940s, earlier than anticipated in this region of Southeast Asia, and the sedimentary proxies indicate large changes in the ecosystem function and capacity for C storage over the past ca. 80 years. Most of these shifts have increased OC accumulation by strengthening autochthonous production or allochthonous OC fluxes, but the implications for other aspects of the C cycle, including catchment soil C loss and greenhouse gas production, need to be accounted for when evaluating the overall impacts of land and hydrological disruption.

KEYWORDS: carbon cycling; palaeolimnology; Tasik Chini; tropical lakes; whole ecosystem experiment

Introduction

Tropical regions are hotspots for carbon (C) cycling and recently the important role of lakes within tropical forests as C sinks has been emphasized, comprising an estimated global organic carbon (OC) sink of ~7.4 Tg C a^{-1} (Amora-Nogueira et al., 2022). Lakes sequester C in their sediments and the amount of C that is deposited and buried depends on the balance between autotrophic (in-lake) production, influx of terrestrially derived C, mineralization and export from the water body (Cole et al., 2007; McGowan et al., 2016; Tranvik et al., 2018). For lakes in the tropical forest biome, the influx of organic matter (OM) into lakes is thought to be substantial and supports higher OC burial rates than other biomes (Amora-Nogueira et al., 2022). However, in tropical lakes that lie along river floodplains, the seasonal flood pulse and riverine connection may be a strong determinant of C cycling (Mitsch et al., 2010). Over a seasonal cycle, the C balance of floodplain lakes can switch from a large allochthonous influx of OC during the flooding phase towards a dominance

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of autochthonous productivity when flooding recedes (Loverde‐Oliveira and Huszar 2007; Pereira et al., 2024). This flood pulse concept emphasizes that floodplain lakes rely on external influxes of C and other nutrients and explains why many floodplain systems are highly productive (Junk et al., 1989). Such seasonal dynamics add complexity when attempting to understand and predict how and why C cycling and C burial in (tropical) floodplain systems are influenced by global environmental change.

Many tropical areas are undergoing rapid economic development which is transforming terrestrial and aquatic ecosystems (Huang et al., 2015; May et al., 2021). Removal of tropical forests for timber and subsequent conversion for agricultural use has been occurring on an industrial scale (Davis et al., 2020). One example of such an agricultural transition is the conversion to oil palm production across broad areas of South East Asia, a central tenet of regional economic development which has increased since the 1980s (Qaim et al., 2020). Such land conversions are associated with increased soil erosion, disruption of the hydrological cycle and agro‐chemical pollution (Comte et al., 2012; Luke et al., 2017). Resource extraction and quarrying is also on the rise in some tropical regions which can strip land cover and invoke major problems with metal contamination and soil erosion (Luckeneder et al., 2021). In temperate regions, agricultural transitions have led to increased rates of C burial in lakes (Heathcote and Downing 2012) which are correlated with increased nutrient supply (Anderson et al., 2020). However, evidence from tropical biomes where land disturbances have occurred relatively recently is scarce and the effects on C cycling and accumulation are less well understood.

Waterways in the tropics are increasingly being disrupted through damming and modification of flows for a number of purposes including power generation, drinking water provision, irrigation and flood prevention (McGowan et al., 2023). Large dams on rivers can reduce fluxes of sediments and nutrients (Kondolf et al., 2018; Maavara et al., 2020) and interfere with C cycling (Maavara et al., 2017). However, on a localized scale many small dams and weirs have been installed in lake in/outlets to regulate water levels (Chen et al., 2022). Such modifications alter the fundamental functioning of floodplain lake systems by impeding the influx of alluvial sediments, enhancing in‐lake cycling of nutrients and increasing macrophyte coverage (Zeng et al., 2018). Therefore, through altering lake ecosystem states (macrophytes versus phytoplankton‐dominated) (van Geest et al., 2003; Velthuis et al., 2018) and the influx and export of C, damming can modify the autochthonous and allochthonous components of floodplain lake C cycling with probable consequences for C burial (Zeng et al., 2022). Damming is also seen to exacerbate the consequences of eutrophication by increasing autotrophic production (Zeng et al., 2023).

Here we focus on an ecologically and culturally important flood pulse wetland, Tasik Chini, in the east of Peninsular Malaysia located in a catchment which has undergone many of the transitions outlined above (Sharip and Jusoh 2010). The ecosystem is a highly productive multi‐basin lake with fringing swamp wetland located in tropical forest. Located within the floodplain of the Pahang River, the longest in Peninsular Malaysia, many of the environmental changes experienced by Tasik Chini typify those in the tropics. Climate is warming and hydroclimate is strongly influenced by monsoonal variability. The flood source, the Pahang River, has been extensively affected both by upland agriculture and soil erosion since the early 1900s and by transition to oil palm agriculture in the lower reaches since the 1980s (Gasim et al., 2009; Tan and Mokhtar 2009). In 1995, a weir was installed on the river connecting Tasik Chini and the Pahang River (Sungai Pahang) which raised lake water levels and reduced water exchange rates. The sub‐catchment of Tasik Chini has also been subjected to varying degrees of local land disturbances including forest removal, rubber and oil palm plantations, and mining for iron. Since these localized changes occur in distinct parts of the lake sub‐catchment, Tasik Chini can be considered as an ecosystem‐scale experiment to distinguish how localized and regional land disturbances in combination with hydrological modification influence C burial in the lake (McGowan and Leavitt 2009; Mills et al., 2017). The aims of the study were therefore to conduct a multi‐basin sediment core study to allow us to understand the mechanisms by which land use, climate and damming influence C burial as well as to develop a realistic estimate of whole‐basin C burial in Tasik Chini.

Site description

Tasik Chini, located in the state of Pahang in Peninsular Malaysia, has a UNESCO designation for its unique cultural heritage in recognition of the indigenous Orang Asli communities who live at the lake margins. Comprising several interconnected basins, Tasik Chini is located beside and connected to the Sungai Pahang [rivers are Sungai (Sg.) in Bahasa] via the Sg. Chini outflow (which becomes an inflow during the flood season) (Fig. 1). Several smaller local rivers also drain the local watershed (relief up to 200 m) into the lake, including Sg. Melai, Sg. Jemberau and Sg. Gumum. The lake is located in an area of humid tropical climate with a temperature range of 21–32°C and total annual rainfall averaging 2700 mm (Harris et al., 2014). Rainfall in Peninsular Malaysia is driven by the southwest (May to September) and northeast (November to March) monsoons, but the northeast monsoon delivers greater quantities of rainfall to Tasik Chini (Gasim et al., 2009). The Sg. Pahang is the longest river in Peninsular Malaysia (495 km length) and drains a 27 000‐km^2 basin spanning the Titiwangsa mountain range in the spine of the Peninsula into the South China Sea (Tan and Mokhtar 2009). Tasik Chini therefore receives water from several small local rivers and from the much larger Sg. Pahang and the relative contribution of these sources may vary seasonally and interannually.

As one of the few natural lakes in Peninsula Malaysia, Tasik Chini is important for biodiversity. There is 2 km^2 of open water with a maximum depth of ~2.7 m (Table 1) and 7 km^2 of freshwater swamp and swamp forest. There are ecologically important fringing wetland communities such as *Lepironia*‐dominated reed beds and Rasau swamps (*Pandanus heliocarpus*) which form large floating islands. Open water vegetation comprises the floating‐leaved *Nelumbo nucifera* (water lotus) and the invasive submerged macrophyte *Cabomba furcata* which has increased in recent decades (Shuhaimi‐Othman et al., 2008; Rafidah et al., 2010; Sharip et al., 2012). The natural cycle is for macrophyte and emergent vegetation growth during the wet season (November to February), plant reproduction (*Lepironia, N. nucifera*) over the dry season (May to September) and die‐back until the next monsoon period. Since the installation of an outlet weir in 1995 CE on the Chini River, water levels in Tasik Chini have been consistently higher and drowned the large areas of *Syzygium*‐dominated swamp forest (Rafidah et al., 2010). The weir has stabilized flows but larger floods from the Sg. Pahang overtop and enter the lake during most wet seasons. The primary land cover in the immediate area of Tasik Chini is lowland dipterocarp forest, but to the eastern side of the lake several areas have been

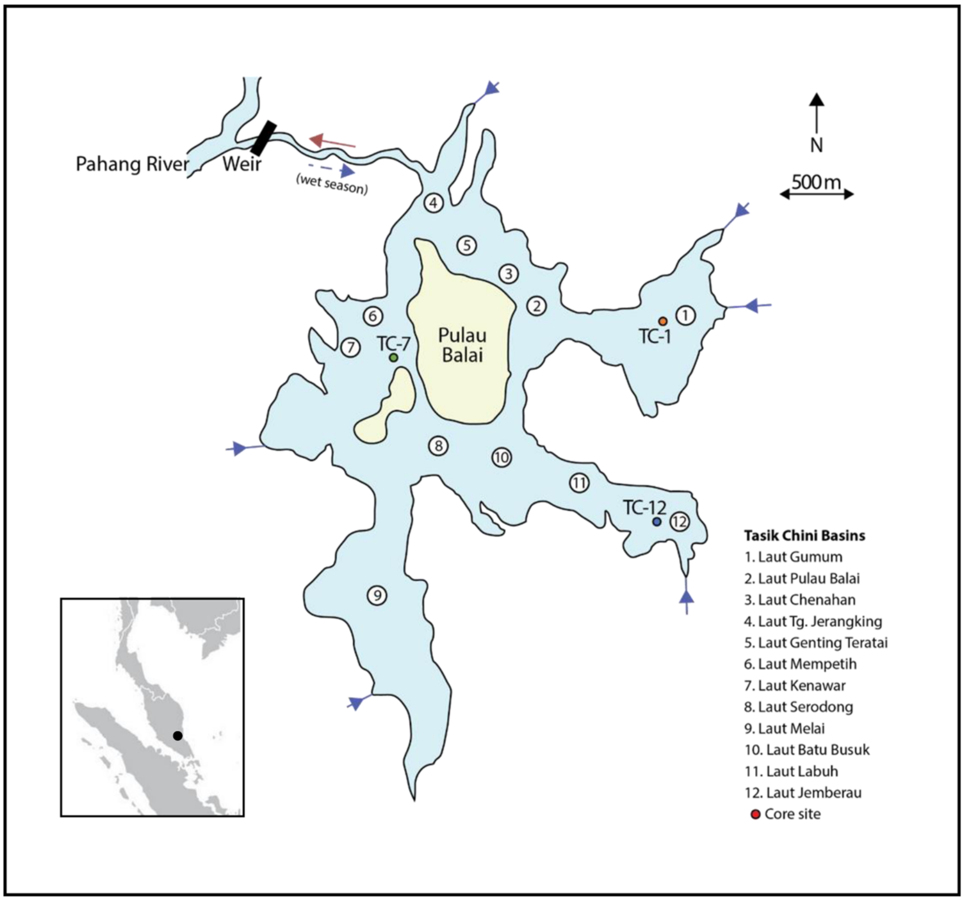

Figure 1. Location of the named sub-basins (Laut = sea) in Tasik Chini. The sites of the dated cores (TC-1, TC-7 and TC-12) are indicated by the coloured circles and the inflows/outflows are indicated by the blue/red arrows. The green sites are floating islands (pulau) of Rasau (*Pandanus helicopus*). The inset map indicates the location of Tasik Chini within Peninsular Malaysia. [Color figure can be viewed at wileyonlinelibrary.com]

Table 1. Coring locations and depths.

Core name	Latitude N	Longitude E	Coring depth (m)
TC1A	03°25′59.40	102°55′30.48	2.5
TC2A	03°26′01.98	102°55′06.80	2.3
TC5A	03°26′26.34	102°54′48.84	1.8
TC7A, 7B	03°26′00.18	102°54′38.04	1.6
TC9A	03°24′51.90	102°54′44.94	1.4
TC11A	03°25′24.90	102°55′22.02	2.5
TC12A	03°25′19.74	102°55′39.06	2.7

cleared for rubber and oil palm plantations, a tourism resort and mining of iron ore (Fig. 2). Typical of tropical forest soils, phosphorus concentrations are low but substantial quantities of potassium (K) are eroded from the catchment (Mir et al., 2015). The larger catchment of the Sg. Pahang has also been influenced by agriculture, mining, residential development, urbanization, logging and industrial activity and experiences high levels of sedimentation, pollution and ecosystem degradation (Mir et al., 2015) and so the periodic connection to this river is probably a pollutant source into the lake.

Previous palaeolimnology at Tasik Chini has focused on site 12 in the eastern part of the basin (Fig. 1), where substantial rises in benthic diatoms since ca. 1940 indicate water level drawdown and swamp encroachment, followed by an inferred decline in water quality associated with the spread of invasive *C. furcata* (Briddon et al., 2020). C isotope ratios indicate that the weir installation in 1995 led to increased autochthonous production, but since basin 12 is the most hydrologically isolated within the wetland, it is not known whether this is a general pattern (Briddon et al., 2020). Sediment cores from Tasik Chini have also been used for analysis of spheroidal carbonaceous particles (SCPs) to establish their use as a chronostratigraphic marker in the Southeast Asia region (Engels et al., 2018); regional increases in SCP fluxes were established to have occurred ca. 1960 CE.

Methods

Sediment coring and fieldwork

Sediment cores were collected from seven sites across the lake in August 2015 using a UWITEC 1-m gravity corer from a boat (Table 1). Coring sites were selected to represent the different parts of the lake basin, and numbered consistent with the Tasik Chini Research Centre basin designations (Fig. 1, TC codes). Duplicate cores (A and B) were collected at each site and the longest core was chosen for further analysis, except for TC7 where more material was needed for analyses and so both cores TC7A and TC7B were used. Cores were sectioned at 1-cm intervals in the field and split into duplicate samples for refrigerated or frozen storage. Samples from around the lake and catchment were collected from representative plants and soils including oil palm, water lotus and various trees and plants (see Supplementary Information (SI) 1, 2 and 3).

Sediment chronologies

Chronologies for three cores were derived from ^{210}Pb and ^{137}Cs dating. Analyses were conducted at University College

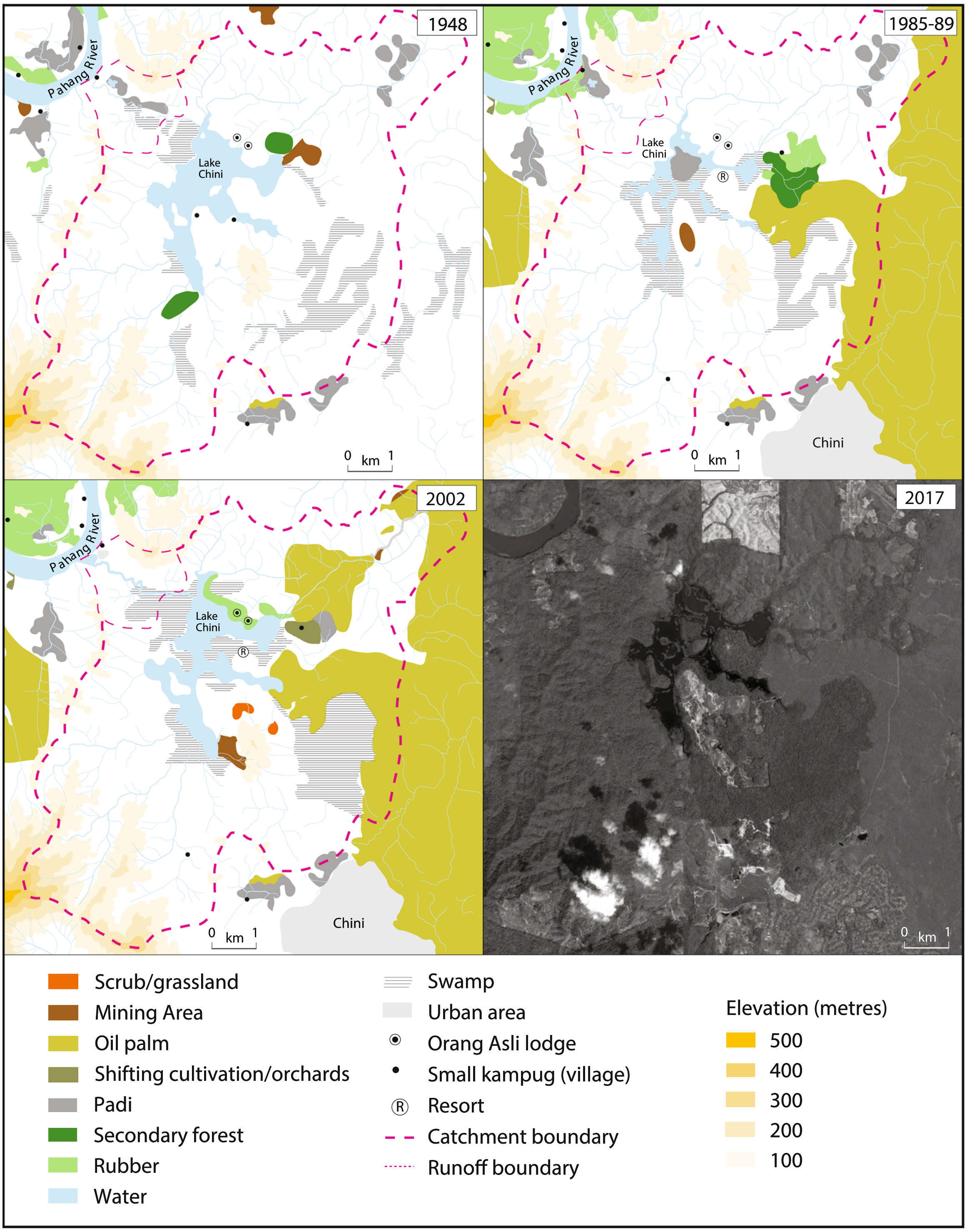

Figure 2. Historical and current land use. Top-left: summary of historical maps from 1948 (Survey Department, Federation of Malaya No. 218-49, prepared from air photographs and existing, limited ground survey data). Top-right: 1985–1989 Director of National mapping 1:50 000 restricted map, Malaysia, published in 1992 and compiled from aerial photos taken in 1985 and field surveys in 1989. Bottom-left: 2002 from the mapping digitization study of Sujaul et al. (2010). Bottom-right: 2017 Google Earth imagery (image taken 3 October 2017). [Color figure can be viewed at wileyonlinelibrary.com]

London (TC1A; published in Engels et al., 2018), the St Croix Watershed Research Station (TC12A, published in Briddon et al., 2020) and the University of Liverpool Environmental Radioactivity Laboratory for TC7A (^{210}Pb dating reports in SI 2). The constant rate of supply (CRS) model was used to derive the chronology as described in SI 2. To facilitate cross-core comparisons, analysis of SCPs was conducted on all cores using the methods in Engels et al. (2018) and the results are expressed in concentration (number per gram of dry mass, # gDM^{-1}). To establish a chronology for core TC7B, the loss-on-ignition (at 550°C, LOI_{550}) profiles (see below) from dated core TC7A were compared to TC7B to match similar change points to specific dates (methods in SI 2).

Carbon proxies and accumulation rates

Analyses of C and nitrogen (N) isotope ratios ($\delta^{13}C$) were conducted on three cores (TC1A, TC7A and TC12A at 1-cm intervals) and on the soil and plant samples from the catchment; the results of the analyses for TC12A are presented in Briddon et al. (2020). Samples were freeze-dried (or first air-dried for the plant samples) and around 0.5 g of sample was added to 5% HCl to remove any carbonates before rinsing with deionized water, drying at 40°C and grinding in agate. The prepared samples were weighed into tin capsules to provide ~500 µg C for analysis. The samples were combusted using a Costech ECS4010 elemental analyser to measure %C and %N, calibrated using an internal standard (BROC2), and the gas passed on-line to a VG TripleTrap and Optima dual inlet mass spectrometer. C isotope data are reported as per mil (‰) deviations of the $^{13}C/^{12}C$ ratio ($\delta^{13}C_{org}$) calculated to the VPDB scale using within-run laboratory standards BROC2 and SOIL A calibrated against NBS-19 and NBS-22. Analytical reproducibility for the within-run standards was <0.1‰ for $\delta^{13}C$.

LOI analysis of sediments was conducted on all cores at 1-cm intervals following Heiri et al. (2001) and % LOI_{550} and % LOI_{925} were used to estimate OM and calcium carbonate content of the sediment, respectively. The % LOI_{925} was below the detection errors of the method (median value of 1.9% for all cores). The LOI analyses were conducted on volumetric (1 or 2 cm^3) aliquots which allowed the sediment density to be calculated. Using the CRS dating models with linear interpolation between contiguous dates for the dated cores, we estimated dates for each sediment layer and then dry mass accumulation rates (DMARs, g cm^{-3} a^{-1}) (Engstrom and Rose 2013). Organic C accumulation rates (OCARs) were estimated by correcting for either the %C as estimated from elemental analysis (above) or from % LOI_{550} by applying a correction factor of 0.469 to convert OM to C (Engstrom and Rose 2013); the specific methods used are indicated in the Results section.

Sedimentary carotenoid pigments were analysed to reconstruct changes in abundance and composition of phototrophic assemblages of algae and cyanobacteria, due to pigment affiliation to particular taxonomic groups (McGowan 2023). Pigments from freeze-dried samples were extracted from cores TC7B, TC1A and TC12A in a mixture of acetone/methanol/water (80:15:5), filtered and separated using the modified method of Chen et al. (2001) with an Agilent 1200 series quaternary pump, autosampler, ODS Hypersil column (250 × 4.6 mm; 5-µm particle size) with photo-diode array (PDA) detection. Pigments were expressed as nmol pigment g^{-1} OM as determined by % LOI_{550} (Heiri et al., 2001). The HPLC device was calibrated using commercial pigment standards from DHI (Denmark) and pigments from cyanobacteria (canthaxanthin) and siliceous algae (diatoxanthin) were selected for this study.

Soil erosion proxies

To indicate possible soil erosion, we used K as it is abundant in the soils around Tasik Chini (Mir et al., 2015) and titanium (Ti) as a conservative element that is used as an indicator of minerogenic catchment inputs (Rose et al., 2004). Freeze-dried sediments from cores TC7A, TC1A and TC12A were ground, placed in plastic pots of 27 mm diameter and covered with Prolene film (4 µm in thickness). X-ray fluorescence (XRF) analysis was conducted on a Panalytical Epsilon 3XL with Omnion calibration. The elemental concentrations are expressed in ppm using Mackereth's principle that accumulation rate is proportional to mineral element concentration (Mackereth 1966). We also conducted grain size analysis on the sediments to help identify the provenance by digesting wet sediment in H_2O_2 in a water bath at 80°C for 2 h, centrifuging, rinsing and adding sodium hexametaphosphate (Calgon). Samples were run through a Coulter Particle Size Analyzer and median grain size was calculated to give an integrative single measure of grain size.

Archival data

The earliest maps of the area with land cover information are from 1948 CE when the Survey Department (Federation of Malaya) conducted aerial surveys supplemented by some limited ground surveys. The next national mapping exercise was conducted with aerial surveys in 1985 CE and follow-up field surveys in 1989 CE by the Director of National Mapping to produce a 1:50 000 restricted map. Land use and land cover (LULC) changes from restricted topographic and land use maps were digitized into a Geographic Information System (GIS) by Sujaul et al. (2010) to provide evidence of LULC changes between 1984 and 2002 CE. Subsequently, satellite imagery is available via Google Earth with more detailed surveys in selected publications (Akhir et al., 2023). The information from these sources was compiled to construct a timeline of LULC change since 1948 CE (Fig. 2). Other historical sources were also referenced to determine the timing of key events in the lake history.

Composite temperature and rainfall records from the 0.5 × 0.5° grids around Tasik Chini (centred on 3.25°N, 102.75°E) were accessed from the Climate Research Unit's TS4.02 global dataset (Harris et al., 2014). The gridding method used for Version 4 of this product is not documented in Harris et al. (2014), but can be accessed via the Google Earth Interface (TMP and PRE only) tool within the Release_Notes_CRU_TS4.00.txt. Monthly mean temperature and total precipitation data were available from 1900 to 2017 CE and trends were assessed by running a weighted averaging smoother through each dataset averaged over 100 sample intervals. The trends in temperature and precipitation during individual months were also explored using a 5-year weighted-average smoother to determine long-term trends during the wet (November to March in this region) and dry seasons (see SI 3).

Numerical analyses

To explore relationships among the sedimentary and climate variables, principal component analysis (PCA) was conducted on 11 sedimentary variables: sediment density, %C, %N, C/N, OC accumulation rate, K, Ti, median grain size, $\delta^{13}C_{org}$, diatoxanthin and canthaxanthin; and two meteorological variables: January rainfall and May temperatures (the highest months for rainfall and temperature, respectively). PCA was conducted separately on each lake dataset. To ensure that the $\delta^{13}C_{org}$ values were positive, 35‰ was added to the ratios and a 5-year running average was applied to the meteorological variables. All variables were tested for homogeneity of variance and to reduce skewness a log $(x+1)$ transformation was applied to each before PCA. Due to the length of the meteorological records, analyses were conducted only on data since 1900 CE. The analysis was performed in CANOCO version 5.05 (Ter Braak and Smilauer 2012).

Results

Archival data

Historical maps indicate that by 1948 CE most of the vegetation around the lake was classified as either jungle or swamp, but there are localized areas of belukar (secondary forest or forest growth on previously cleared or cultivated land) and brush (shrubland) around the inflows on the eastern (TC1, Laut Gumum; laut = an area of 'sea') and southern (TC9; Laut Serodong) basins (Fig. 2). This corroborates anecdotal accounts of forest clearances around Tasik Chini by Japanese troops during the occupation of Malaya (1941–1945 CE) (van der Helm n.d.). By 1985–9 CE the maps indicate agricultural conversion of much of the eastern sub-catchment. There was rubber and oil palm with some secondary forest regrowth covering most of the TC1 sub-catchment and oil palm in the northern half of the TC12 (Laut Jemberau) sub-catchment. There was evidence of quarrying or land cutting on the elevated land between the TC12 and TC9 sub-catchments, suggesting that surface mining had occurred, corroborated by evidence from Sujaul et al. (2010) who notes an increase in mining between 1984 and 1990 CE. A tourist resort was established between basins TC1 and TC12 sometime before 1985 CE. By 2002 CE mining activity was well established up to the shores of TC9 and the plantations of oil palm had expanded in the sub-catchment of TC1. The abandoned quarry from the earlier map was reactivated to start iron-mining activities in early 2005 CE around the Jemberau River draining into TC12 (Dom et al., 2016) and so satellite imagery on Google Earth indicates an expansion of mining activities between TC9 and TC12, with an expanse of stripped mining land visible by 2017 CE and the continued presence of plantations in the east of the catchment.

As well as land use, the maps indicate large changes in the aerial extent of water between 1948 CE when all basins were mapped as being connected by open water in comparison with the 1985–9 CE maps when areas of swamp separated basins TC12 and (partly) TC9 from the rest of the water body. By 1995 CE a weir had been installed to stabilize and raise water levels and improve conditions for eco-tourism (as supported by the new resort). This led to an increase of around 200 ha in water cover by the year 2000 CE (Sujaul et al., 2010) and drowned vegetation is visible at the perimeter of the lake in the most recent Google Earth imagery (Fig. 2). Long-term temperature records are available after 1915 CE and show a sustained reduction in temperatures between 1945 and 1985 CE and then a consistent rise in temperature above the long-term average after 1990 CE, with the warmest months being April, May and June (SI 3). Long-term trends in rainfall are mostly stable apart from a reduction around 1975 and 1995 CE, driven mainly by lower quantities of rainfall in the highest rainfall months (November, December and January).

Sediment chronologies and comparison among cores

Based on the ^{210}Pb chronologies, the mean sediment DMARs since 1860 were ordered as TC7A ($0.0628 \pm 0.0267\,g\,cm^{-2}\;a^{-1}$) < TC12A ($0.0821 \pm 0.0523\,g\,cm^{-2}\;a^{-1}$) < TC1A ($0.1125 \pm 0.0729\,g\,cm^{-2}\;a^{-1}$) (SI 2 and in Engels et al., 2018, Briddon et al., 2020). Sedimentation rates increased in all the dated cores with mean DMARs between 1860–1945 and post-1945 increasing 1.6-fold in the undisturbed site (TC7A), 4.3-fold in the site with the longest land disturbance history (TC1A) and 2.4-fold in TC12A with the later land disturbance history. The boundary for the first appearance of SCPs was dated at 70 years (1945 CE) in TC1A and 75 years (1940 CE) in TC7A, while it was much later in TC12A (1995 CE).

SCPs were detected in all the cores (Fig. 3), and an increase in their accumulation in sediments should be a consistent chronostratigraphic marker of the Anthropocene, providing a common time horizon for the escalation of industrial fossil fuel burning around 1950 CE (Rose 2015). Since not all the TC cores were dated, it was not possible to estimate SCP accumulation rates for all cores. Instead, the depths of first SCP appearance were used in an attempt to pinpoint a common chronostratigraphic marker across all lake cores. Based on the LOI-matched chronology (Fig. 4), the earliest appearance of SCPs was in TC7B at around 30 cm depth (corresponding to around 25 cm depth in TC7A) which was around 1929 ± 7 CE. The first appearance date in TC1A was 1952 ± 13 CE (31 cm depth) while it was much later in TC12A (1985 ± 6 CE; 22 cm depth). Comparing all cores with and without chronologies the depth of appearance of SCPs was variable, being deepest in TC9A and then TC5A (basins on the western part of the lake) and shallowest in TC11A and TC12A (basins on the east).

In terms of sediment properties, the cores located in the southern and eastern bays of the lake (TC9A, TC11A, TC12A) furthest from the in/outflow (Sg. Chini) had lower and more stable sediment density and higher % LOI_{550} (Fig. 4). Sediment density was highly variable and % LOI_{550} was lowest in sites aligned with the in/outflow (TC2A, TC5A). In several sites there were distinctive step changes in % LOI_{550}. In terms of downcore changes, the trend was for % LOI_{550} to either be lower (TC1A, TC2A and TC5A) or higher (TC11A, TC12A) in upper part of the cores relative to the historical baseline LOI_{550}. In other sites there was no obvious long-term deviation from the historical baseline. However, all of the cores exhibited at least one period of a sustained reduction in LOI_{550} lasting for varying parts of the core length, implying a sustained shift in OC or OM sedimentation patterns during certain periods of each basin's history.

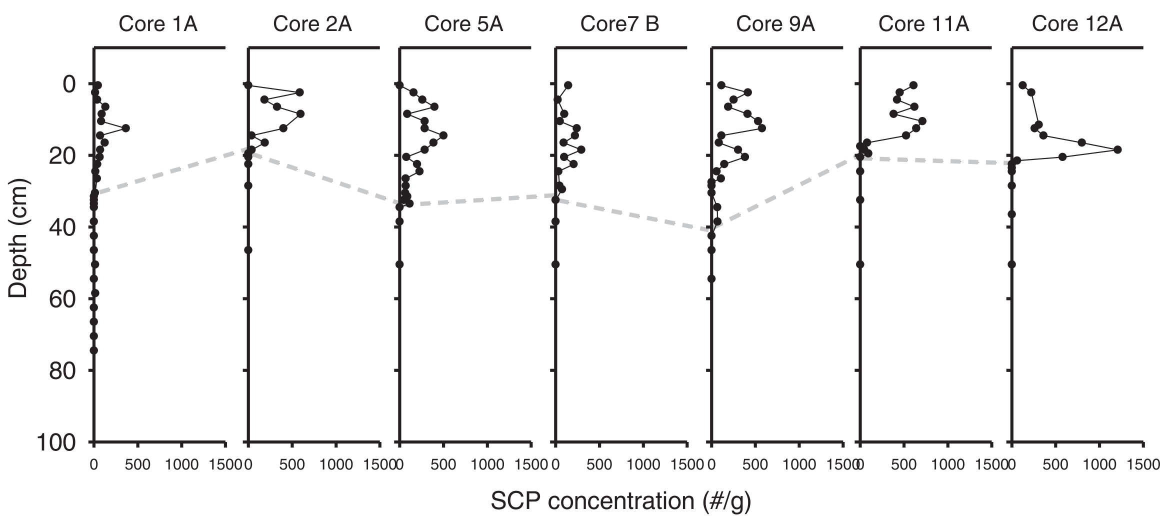

Figure 3. SCP concentrations in seven sediment cores from Tasik Chini with the first horizon of SCP appearance marked with the dashed grey line. Core locations are indicated by the numbers in Fig. 1.

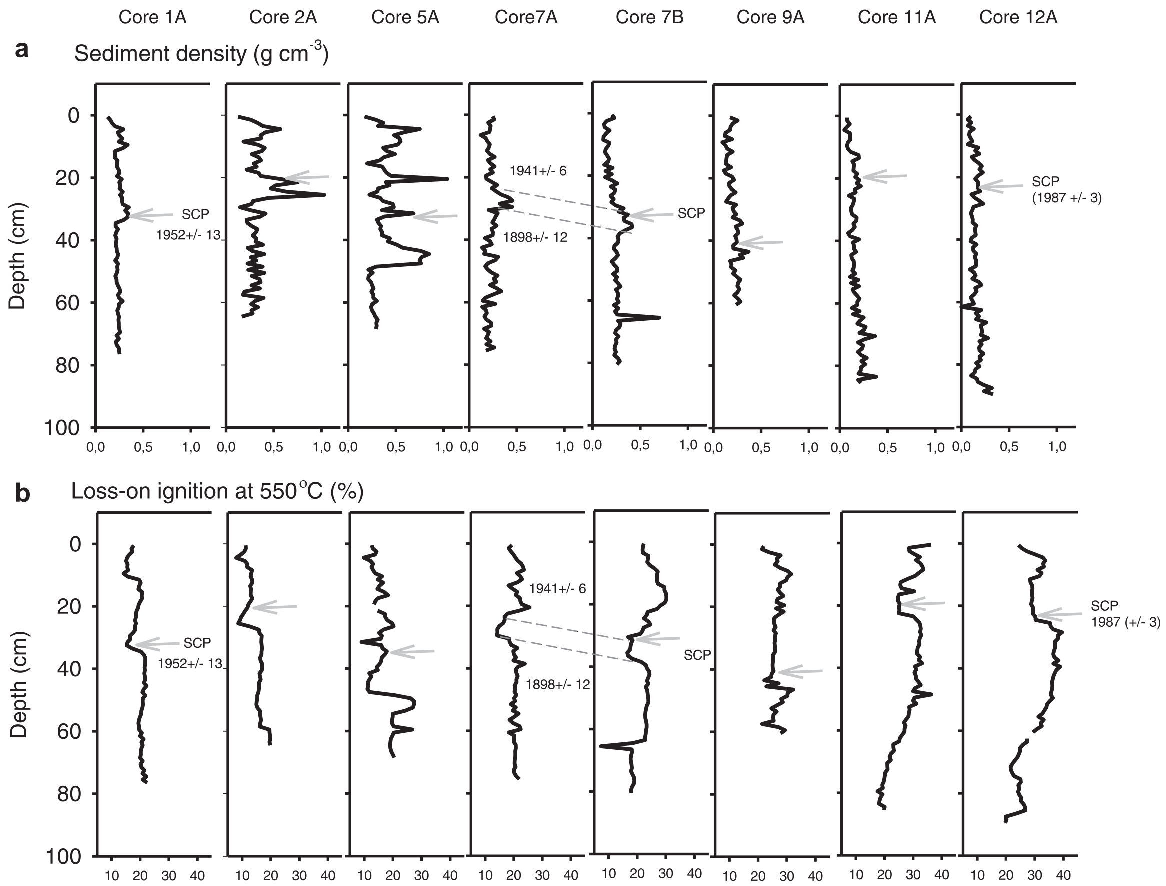

Figure 4. Sedimentary analyses including (a) dry density and (b) loss on ignition (LOI) at 550°C as an estimate of organic matter content in eight sediment cores from Tasik Chini from seven locations as marked on Fig. 1. The cores from location 7 were taken close to one another as 'replicate' sequences at that site.

Temporal trends across the Tasik Chini basin

Indicators of land disturbance

Ti concentrations increased significantly in sediments of all three dated cores, but the rate of increase was substantially higher in TC1A (the most disturbed site; Fig. 5). Specific increases in [Ti] in TC1A occurred in the 1940s and in the late 1970s, coincident with the identified periods of land disturbance (forest removal, rubber/oil palm) (Figs. 2 and 5). In TC12A there was a very high peak in [Ti] after 2010, after mining activity accelerated, whereas [Ti] increased after ca. 1990 CE in TC7B. The median grain sizes declined after ca. the 1920s to 1930s in TC7B and TC1A, apparently unrelated to identified land use changes, whereas the trends were very different in TC12A, which had overall larger grain sizes and a rise in median grain size which started in 1880 CE, declining values between 1940 and 1980 CE, encompassing the period of water level drawdown, and a rise in values since the 1990s to a historical maximum after the 2000s. Potassium concentrations [K] did not change significantly in the TC7 record apart from a slight lowering of concentrations during the low rainfall/water drawdown period (Fig. 5). In contrast [K] increased in TC1A, rising slightly after ca. 1940 CE and distinctly after 1975 CE and declined significantly in TC12A, especially after 1940 CE.

Indicators of carbon cycling

In the early part of the core records, C/N ratios from TC7A and TC1A were similar (~12), but much higher (~18) in TC12A (Fig. 5). All three records show an overall trend towards lower C/N ratios, but with distinctive temporal trends. The main response in TC7A was a steady decrease in C/N ratios after 1980 CE and a stabilization of the ratios after the installation of the weir. C/N shifted earlier in TC1A with a small increase during the 1940s when the first forest clearances occurred followed by a steep decline in the late 1990s around the time of weir installation. The C/N ratios in TC12A are distinctive, starting at 18 and then decreasing, at an accelerated rate after 1940 CE to reach values of around 10 in the late 2000s. Consequently, during the 2000s, the C/N ratios in all three lakes were around 10 or slightly lower. The $\delta^{13}C_{org}$ trends are quite different among the basins; the values are low at the base of TC7A (–30‰) while TC1A and TC12A are around –32‰. In TC7A there was a sustained increase (1‰) in $\delta^{13}C_{org}$ after 1940 CE, but a distinctive and sudden shift to lower $\delta^{13}C_{org}$ between 1970 and 1990 CE (–32‰ in 1975 CE), coincident with the low rainfall period. In TC1A there was an abrupt increase in $\delta^{13}C_{org}$ which started in 1940 CE and underwent a step change in 1950 CE, around the time of the first forest clearances, towards consistent values of around –31‰ until 1990 CE. After the weir installation there was an abrupt decrease in $\delta^{13}C_{org}$ in the late 2000s. $\delta^{13}C_{org}$ changes in TC12A were more gradual and characterized by a slow rise in $\delta^{13}C_{org}$ after 1970 CE during the period of low rainfall towards a peak (–31.5‰) in 1990 CE and then afterwards a transition to lower values with a minimum of –33‰.

The biplot of $\delta^{13}C_{org}$ versus C/N ratios helps to identify the sources of sedimentary OM and also demonstrates that basins TC7, TC1 and TC12 in Tasik Chini had distinctive trajectories of OM change (Fig. 6). Most of the samples lie in a space between terrestrial plants and lacustrine algae, suggesting that sedimentary OM is a mixture of these sources (Meyers and Teranes 2001). The main trend was for all three cores to move

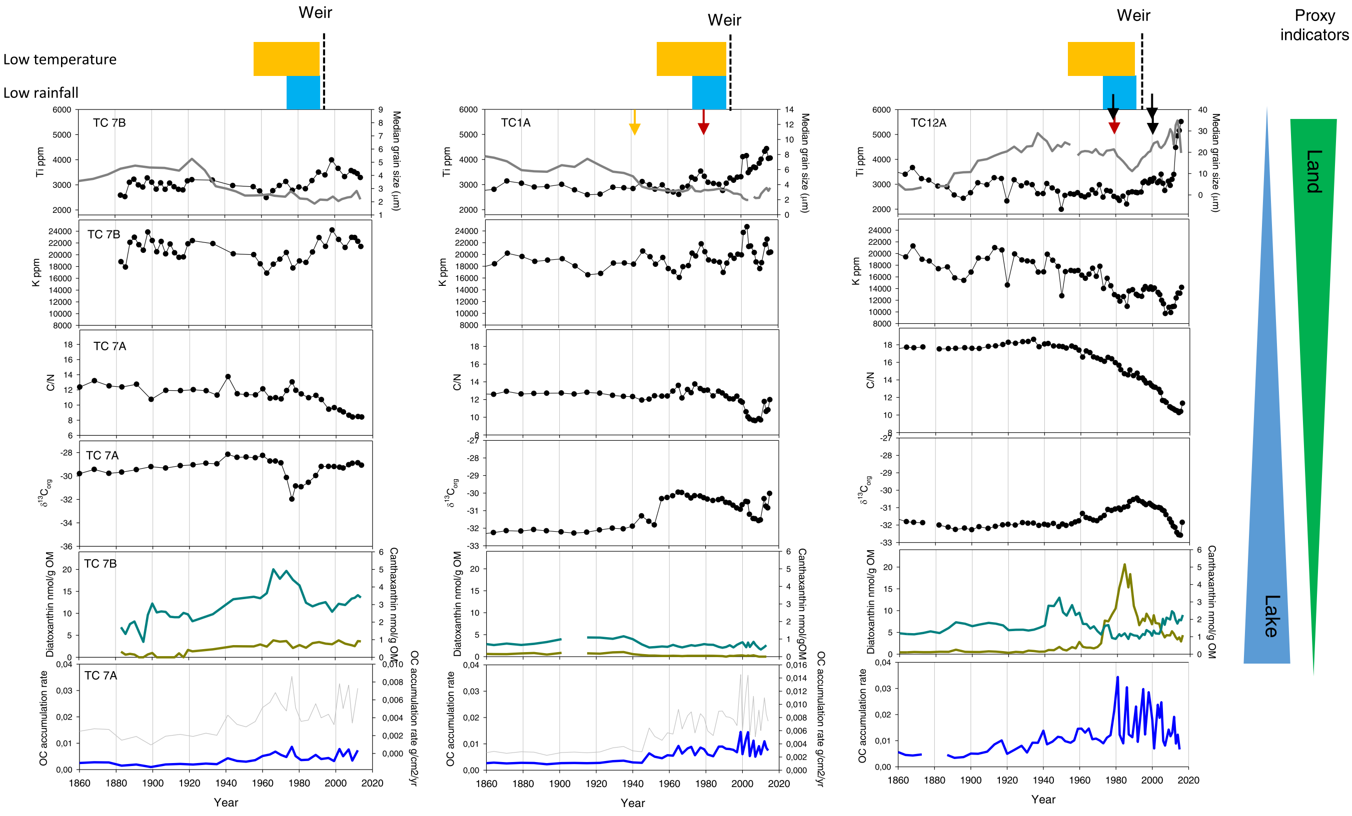

Figure 5. Multiple proxies in cores from site 7 (TC7A and TC-7B; low land disturbance), site 1 (TC-1A; early land disturbance) and site 12 (TC12A; late and intensive land disturbance) ordered from top to bottom panels by the degree to which they are linked to allochthonous (land) versus autochthonous (in-lake) processes: titanium concentrations (black) and median grain size (grey); K concentrations; C/N ratio; $\delta^{13}C_{org}$; carotenoid pigments diatoxanthin (siliceous algae, yellow) and canthaxanthin (cyanobacteria, cyan); and OC accumulation rate (blue, left axis) with exaggeration line in grey (right axis). Scales for *y*-axes are identical across the three sites. The bars above the figure indicate extended periods of low precipitation (blue) and low temperatures (orange). The dotted lines indicate the time of weir installation and arrows indicate key land disturbance points of forest removal (orange arrow), oil palm introduction (red arrow) and mining (black arrow; double arrows indicate intensive mining). [Color figure can be viewed at wileyonlinelibrary.com]

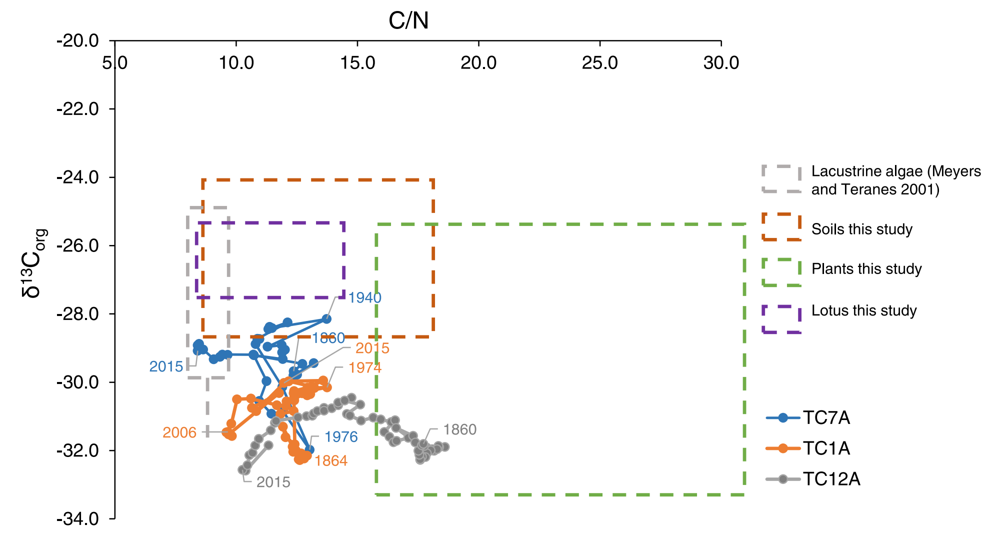

Figure 6. $\delta^{13}C_{org}$ and C/N ratios as measured in sediment samples from cores TC7A (blue), TC1A (orange) and TC12A (grey). The ranges of $\delta^{13}C_{org}$ and C/N ratios as measured on lacustrine algae material (Meyers and Teranes 2001) as well as samples of soil (red square), terrestrial plants (green square) and aquatic plants (water lotus, *Nelumbo nucifera*; purple square) taken from Tasik Chini are provided for comparison. See SI Table 1 for more information on the soil and plant samples. [Color figure can be viewed at wileyonlinelibrary.com]

towards the lacustrine algae part of the diagram in recent decades, but this trend was strongest in TC12A. For TC7A and TC1A, there was more variability in $\delta^{13}C_{org}$ which could indicate a more variable supply of OM from soils (higher $\delta^{13}C_{org}$) or terrestrial plants (lower $\delta^{13}C_{org}$).

Biomarker pigments for phototroph production from siliceous algae (diatoxanthin) and cyanobacteria (canthaxanthin) can, when normalized to the OM content, estimate the proportion of OM that derives from primary production of specific lake-dwelling taxa (McGowan 2013). Pigments in all cores showed quite different temporal patterns. In TC7A, diatoxanthin gradually rose from the 1920s onwards while increases in canthaxanthin (cyanobacteria) pigments were more prominent after the 1940s, and peaked around the time of lower rainfall. In TC1A, diatoxanthin and canthaxanthin abundance declined after 1940 CE, coincident with the first forest removal and abrupt shifts in $\delta^{13}C_{org}$. In TC12A, however, there was an increase in the relative contribution of autotrophic pigments to the OM pool, with an abrupt rise in cyanobacterial pigments after 1940 CE succeeded by a slow return to previous levels by 1970 CE, followed by a rise in diatoxanthin which peaked in 1985 CE and declined by the mid-2000s when canthaxanthin started to increase once more. The rises in cyanobacteria preceded the first oil palm plantations around TC12, but the rise in siliceous algal pigments coincided with the inferred lake level drawdown during the low rainfall period (1975–1990 CE).

Temporal trends in organic carbon accumulation rates

The mean 'baseline' (i.e. pre-1945 CE) OCAR sedimentation was more than twice as high in TC12A as in TC7A and TC1A; the rates were $22.4 \pm 8.1\,g\,m^{-2}\,a^{-1}$ in TC7A, $28.3 \pm 3.4\,g\,m^{-2}\,a^{-1}$ in TC1A and $69.9 \pm 27.6\,g\,m^{-2}\,a^{-1}$ in TC12A. After 1945, mean OC sedimentation rates were at least double the baseline levels in all of the basins; the rates were $51.1 \pm 22.4\,g\,m^{-2}\,a^{-1}$ in TC7A, $77.4 \pm 28.3\,g\,m^{-2}\,a^{-1}$ in TC1A and $149.8 \pm 69.9\,g\,m^{-2}\,a^{-1}$ in TC12A. There was a synchronous but small rise in OCARs after ca. 1940 in TC7A and TC1A and more distinctive peaks in OCARs after 2000 CE. For TC12A there was a slowly rising trend in OCARs since the 1910s with a marked step change towards higher and very variable OCARs around 1975 CE with a highly variable but declining trend thereafter.

Summary of temporal trends

The PCA helps to identify the main periods of change in each basin and to establish whether temporal variability in OCAR is associated with evidence of allochthonous (e.g. precipitation, soil erosion indicators, high C/N ratios) versus autochthonous C sources (e.g. pigments, low C/N ratios) (Fig. 7). In TC7 (A and B), which retained a connection to the flood pulse and had limited local catchment disturbance, there were two main periods of change: (i) before 1941 CE when median grain size and sediment density were higher and (ii) after 1941 CE when sediments had higher %C, %N and OCAR and carotenoid pigments, but moved gradually from lower [Ti] and [K] towards increasing concentrations of these elements after the 1990s when temperature, precipitation and $\delta^{13}C_{org}$ increased. There is no correlation between OCAR and either soil erosion indicator (Ti, K) or the C/N ratios and $\delta^{13}C_{org}$ in TC7, but there is a negative relationship between median grain size and OCAR and a positive relationship with the phototrophic pigments and %C and %N content. In TC1A there is a clear separation into three time periods: (i) before 1940 CE when median grain size, %C and %N, diatoxanthin and canthaxanthin concentrations were higher; (ii) between1941 and 1991 CE when sediment density, $\delta^{13}C_{org}$ and C/N ratios were higher; and (iii) after 1992 CE when OCAR rose alongside [K], [Ti], May temperatures and December precipitation. In TC1A there is a correlation between OCAR and both the soil erosion indicators (Ti, K) and the meteorological variables (May temperatures and December precipitation) but a negative correlation between OCAR and %C, %N, median grain size and carotenoid pigments. In TC12A there were only two main phases of distinctive change: (i) before 1975 when K, %C and C/N were high and (ii) after 1975 when there was a rise in OCAR, diatoxanthin and $\delta^{13}C_{org}$ in the 1980s and 1990s followed by sediments that were increasingly enriched in Ti with higher median grain size. In TC12A, the correlations between [Ti], [K] and meteorology (precipitation, temperature) were weaker than in other sites.

Spatial variability in organic carbon accumulation rates

Estimates of OCAR since ca. 1945 CE were made on samples using the % LOI_{550} measurements of C and assuming that the SCP appearance date was a valid chronostratigraphic marker point for ca. 1945 CE in all cores (Fig. 8). The post-1945 CE rate of OCAR was also estimated for the three dated cores using the ^{210}Pb dates. Due to the large discrepancies in SCP versus ^{210}Pb dates in TC12A, there was a more than 2-fold difference in the estimates by each method, but those from TC7A and TC1A were more similar. The OCAR estimates across the basin range from the highest in TC5A (>$160\,g\,m^{-2}\,a^{-1}$) to four times lower in TC11B (<$50\,g\,m^{-2}\,a^{-1}$). Together this leads to a median OCAR for the Tasik Chini basin of $85\,g\,m^{-2}\,a^{-1}$.

Discussion

The estimated median OCAR for Tasik Chini since 1945 CE of $85\,g\,m^{-2}\,a^{-1}$ is in line with the calculations of Amora-Nogueira et al. (2022) for humid tropical forest lakes (median $97\,g\,m^{-2}\,a^{-1}$) and is higher than the median OCARs in

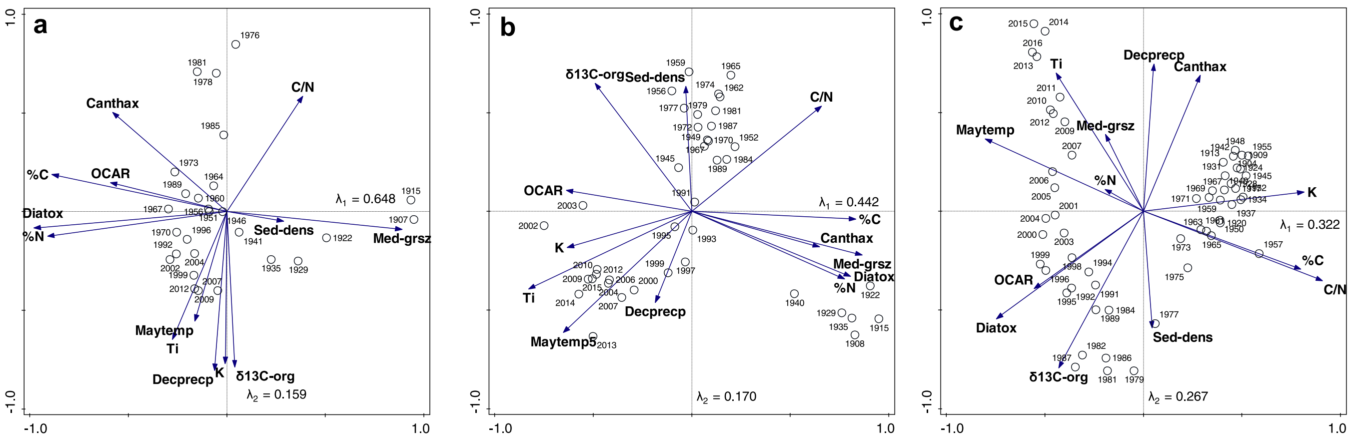

Figure 7. Scores of sediment proxies and meteorological variables from cores TC7A and B (a), TC1A (b) and TC12A (c) on the first two axes of a PCA. Variables included in the analyses are %C (% carbon), %N (% nitrogen), OCAR (organic carbon accumulation rate), C/N (C/N ratio), Sed-dens (sediment density), Med-grsz (median grain size), Ti (Ti concentrations), K (K concentrations), Canthax (canthaxanthin concentrations), diatox (diatoxanthin concentrations), Decprecp (December precipitation, 5-year running mean) and Maytemp (May temperatures, 5-year running mean). The variables were centred and standardized prior to analysis. [Color figure can be viewed at wileyonlinelibrary.com]

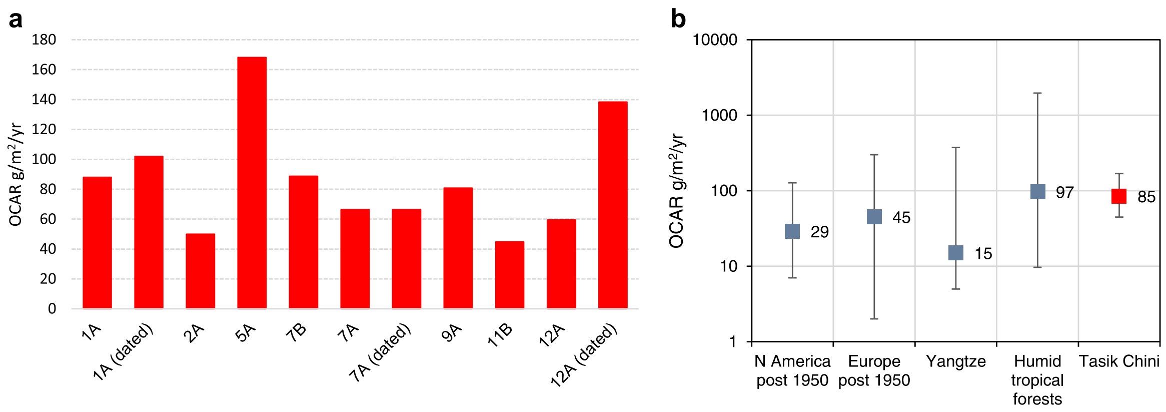

Figure 8. (a) OCARs in the Tasik Chini cores estimated since the first appearance of SCPs in each site and for the ^{210}Pb-dated cores to the period after 1945 (% LOI_{550} method). (b) Median OCAR (±maximum/minimum) from groups of lakes located in different regions and biomes of the world compared with the Taski Chini cores. The studies are from North America (Anderson et al., 2014); Europe (Anderson et al., 2013); Yangtze basin, China (Dong et al., 2012); and lakes in humid tropical forests (last 50–100 years) (Amora-Nogueira et al., 2022). The Tasik Chini data are calculated for the most recent ~70 years (1945–2016). [Color figure can be viewed at wileyonlinelibrary.com]

temperate Europe and North America (Fig. 8). The OCARs from the Yangtze floodplain include many (modified) floodplain basins and yet despite these functional similarities with Tasik Chini, Yangtze lakes had the lowest median OCARs (15 g m^{-2} a^{-1}) (Fig. 8). This suggests that the high capacity of Tasik Chini for C storage is due to the surrounding land cover of tropical forest which provides an abundant supply of OC (Amora-Nogueira et al., 2022). Nevertheless, it is clear from the analyses here that forest cover has been severely disrupted in Tasik Chini and that this disturbance shifts the C balance of the ecosystem. Because the extent of land disturbance ranges from largely undisturbed in the western side of the lake catchment to heavily modified in the east, we can apply the approach of a 'whole ecosystem experiment' for understanding how land transitions affect OCARs and C cycling (McGowan and Leavitt 2009).

Changing land use around Tasik Chini

The historical map analysis confirms previous studies in indicating far more intensive land use on the eastern side of Tasik Chini than on the west. According to RUSLE (Revised Universal Soil Loss Equation) soil erosion modelling, this indicates a very high soil erosion risk in the TC12 and TC1 sub-catchments, whereas most of the western parts of the catchment were at very low erosion risk (Mir et al., 2010; Sujaul et al., 2010). These RUSLE estimates indicate a loss of between 0.10 and 8.39 kg K ha^{-1} a^{-1} from soils in the Tasik Chini catchment (Mir et al., 2015), verifying that [K] should be a useful indicator of soil erosion in this basin. Using the mapping information, important periods of land use change were pinpointed (indicated by arrows in Fig. 5): forest disturbance in the eastern catchment (TC1, TC9) in ca. the 1940s, indicated by secondary forest (belukar) presence in 1948 CE; oil palm and rubber plantations in the sub-catchments of TC12 and TC1 by 1985 CE, as well as mining in TC12 and TC9; by 2002 CE well-established mining activity between TC9 and TC12, oil palm, scrub and rubber plantations at the shores of TC1 and oil palm in the sub-catchment of TC12; and continuation and escalation of mining around TC12 until at least 2016 CE (Dom 2016). Overall, localized land use around TC7 was minimal, in TC1 forest removal began very early (ca. 1940 CE) and escalated in the 1980s, and most land disturbance in TC12 started later (after the 1980s). Although the entire Tasik Chini basin has been subjected to common pressures (escalating pollution from the Sg. Pahang, water level drawdown in the 1970s, weir construction), the variability in land use histories provides a cross-basin comparison for understanding how floodplain lake basins respond to varying duration and intensities of localized land use modification.

Inter-basin comparisons

There was variability in OCAR estimates among the cores (Lin et al., 2022), but little evidence from our data of systematic sediment focusing (no correlation between lake depth and either DMAR and OCAR), as is often observed in deeper lakes (Engstrom and Rose 2013). Therefore, our multi-core analysis can provide a realistic OCAR estimate across this shallow basin without the need for sediment-focusing corrections. Our sedimentary analyses suggest that the characteristics of each sub-basin within the wetland system can modify C cycling and burial. As identified by the historical mapping (Fig. 2) and verified by the sediment proxies (Figs. 3–5), the sub-basins that were most distal from the Chini River in/outflow were hydrologically quite distinctive, becoming largely separated from the main basin some time prior to 1985 CE, and probably driven by the preceding period of low rainfall (Fig. 5). Basin TC12 sediments are more organic and less dense (Fig. 4) and the baseline C/N ratio is higher (~18) than the other basins TC7 and TC1 (Fig. 5), suggesting that C inputs were more dependent on terrestrial and emergent vegetation sources (Fig. 6). This is consistent with the extensive fringing vegetation around the TC12 sub-basin and the higher ratio of perimeter/water area in this narrow part of the system (Hanson et al., 2015). The lower and more stable sediment densities seen in TC12A were similar across other sites located furthest from the flood pulse (TC9A and TC11 A; Fig. 4) indicating a generalized pattern of declining river influence (minerogenic particulate ingress) further away from the source. The C/N ratios of basins TC7 and TC1, which are both closer to the river, indicate higher autochthonous C inputs consistent with their functioning as a flood pulse system, alternating between lentic and lotic conditions with a substantial proportion of their accumulated C deriving from autochthonous productivity sustained by the nutrients/OM delivered during flooding (Pereira et al., 2024). The higher baseline $\delta^{13}C_{org}$ in TC7 implies higher overall productivity or higher soil inputs and both scenarios are possible because TC7 is positioned to be well supplied by the flood pulse from the Sg. Chini which supplies both nutrients for autochthonous production and soil OM from the Pahang River. Given the minimal land disturbance at TC7 it is unlikely that the soil OM source is predominantly local. Overall, the pre-disturbance OCARs were similar in all lake basins, and only slightly elevated in TC12, indicating a similar capacity for C burial across the lake.

The SCP records further corroborate the complex sedimentation patterns in Tasik Chini because the first appearance date of SCPs varies among the cores. SCPs are a useful chronostratigraphic marker in regions where the timing of increase in industrial fossil fuel burning for power generation is known. In this area of SE Asia Engels et al. (2018) used core TC1A from Tasik Chini together with sites from the Philippines and Singapore to establish a significant increase in regional SCP flux at 1960 CE. The first detected SCP occurrences in cores TC1A and TC7B date to 1952 ± 13 and 1941 ± 6 CE, respectively, agreeing with the idea that these basins collected contemporaneous deposits of SCPs. However, the first SCP occurrence in TC12 dated to 1987 ± 3 CE, implying that the TC12 basin did not receive detectable fluxes of SCPs prior to this time. It is reasonable to assume that the Sg. Pahang, the source of the flood waters into the Sg. Chini, could be a significant source of SCPs since it drains a large area including waters from the Titiwangsa mountains, an area which probably receives atmospheric pollutants from the more industrialized western side of the Peninsula. The hydrological isolation of TC12 from the main basin by swamp vegetation by at least the early 1980s would have prevented the ingress of flood-borne particulates. Once rainfall increased (late 1980s), SCP concentrations rose sharply in the sediments, suggesting mobilization of SCPs into TC12, assisted by sediment reworking. Together, the SCP records confirm the complex nature of sedimentation in Tasik Chini and how this has varied over time, and help to verify that a multi-core approach to OCAR assessment is appropriate in this site (Engstrom and Rose 2013).

Temporal trends in soil erosion

The concentrations of Ti and K help to identify the influence of soil erosion in different parts of the basin, and the more complacent rise in [K] and [Ti] in TC7 (undisturbed) than in TC1 (disturbed) confirm that land disturbance increases the flux of soil particulates into the lake basins (Fig. 5). Rises in these elements in TC1 coincide with periods of land disturbance in the 1940s and the 1980s while the increases in [Ti] in TC7 are mostly after 1980 CE and could feasibly be recording both eroded materials transported to Tasik Chini from the Sg. Pahang and materials transported from the eastern side of the lake basin. In TC12 the response is mostly decoupled from known land disturbances; Ti concentrations are stable for most of the record, suggesting that any localized increase in Ti influx from the TC12 sub-catchment was counterbalanced by the declining influence of Sg. Pahang flooding as the basin became more hydrologically isolated. Most striking however is the spike in [Ti] since 2010 CE in TC12 which coincides with a drop in ^{210}Pb activity, indicating the significant influence of (^{210}Pb-depleted) mining deposits on the recent sedimentation in TC12 which would be transported to the basin by the Sg. Jemberau. The long-term decline in [K] in TC12 is consistent with both swamp encroachment and forest removal at this site as terrestrial vegetation requires K to support growth and deforestation would export K from the catchment. Overall, these patterns suggest a combination of localized and flood-borne influxes of Ti and K to the lake basins that was substantially modified depending on the ecohydrological circumstances of the basin.

Land use effects on carbon cycling

The highest OCARs of the dated cores were found in the most hydrologically isolated basin (TC12). The declining trend in the C/N ratio indicates that algal sources of OM have been steadily increasing at this site since around 1940 CE, prior to local land disturbances, corroborated by successive increases in pigments from cyanobacteria, and then siliceous algae (Figs. 5 and 7). In general, OC decays more slowly in lakes with higher water retention times (Catalán et al., 2016), suggesting that a combination of elevated production and increased preservation contributed to the higher OMARs in TC12. Since 1940 CE, diatom records from TC12 indicate a proportional rise in benthic diatoms *Frustulia crassinerva*, *Frustulia rhomboides* and *Brachysira brebissonii* (Briddon et al., 2020), taxa associated with mildly acidic conditions, implying that this pigment increase is due to a rise in benthic rather than planktonic productivity. This pattern indicates a progressively hydrologically isolated basin, and a loss of alkalinity and buffering capacity as the effective drainage area declines and swamp vegetation encroaches, leading to the most productive ontogenetic phase in lake development (Wetzel 1979). Declining flood frequency is known to enhance pigment deposition in floodplain lake sediments (McGowan et al., 2011) and the combination of the meteorologically induced water level drawdown and natural swamp succession has led a step change towards elevated OCARs around 1975 CE (Rasbold et al., 2021; Rogers et al., 2022). However, there is a sustained shift towards more autochthonous productivity in TC12 (Figs. 5 and 6) as well as obvious shifts in the diatom taxa since 1940 CE (Briddon et al., 2020) which suggests that sediment infilling and nutrient influxes from firstly regional (Pahang) and later local (Gemberau) river particulates could have exacerbated the shift towards lentic conditions and influenced water quality and benthic plant cover (Sharip et al., 2014). Overall, the results suggest that hydrological isolation of lake basins can improve conditions for C burial by stimulating production of macrophytes and benthic microbiota and restricting outflow of particulates (Zeng et al., 2018).

The response to land use change in TC1 (the basin subjected to the longest and most intensive land disturbances) was very different and marked by a rise in C/N after 1940 CE, implying an increase in OM deriving from soils or terrestrial plants which led to a decline in the relative contribution of C from autochthonous pigments (Fig. 5) (Chen et al., 2017). This implies that more of the sedimentary C came from allochthonous sources resulting in a rise in OCARs. Therefore, the OCARs in TC1 appear to be more directly driven by an increase in externally derived OC, a pattern which is confirmed by the correlations in the PCA (positive relationship with [K], [Ti] and precipitation, and negative relationship with pigments, %C and %N) (Fig. 7). This means that in TC1, sediments with lower OM content were being deposited at a faster rate resulting in a higher net rate of OCAR. The rise in sediment densities and reduction in LOIs during the first land disturbance in World War II (early 1940s) agrees with this interpretation (Fig. 4) and it appears that the basin functioned in this way until installation of the weir (see below).

In TC7 where localized land use was limited, OCARs rose in 1940 CE, but OCAR was correlated with a rise in %C and %N and phototrophic pigments (Fig. 7). The first identifiable C cycling response in TC7 was a slight increase in pigments around 1920, higher OCARs after 1940, but minimal rises in C/N ratios which suggests increased autochthonous productivity. Since a rise in $\delta^{13}C_{org}$ occurred independent of localized land disturbance at this site we infer it was prompted by an increase in nutrient supply from the Pahang River or from the other disturbed areas of Tasik Chini in basins TC1 and TC9. This increase in autotrophic production resulted in rather minor increases in OCAR. However, shifts in the phototrophic assemblages as early as the 1920s could be a response to land transitions in the broader Sg.

Pahang basin, for example the spread of rubber cultivation since the late 1800s in Malaysia and the development of hill plantations for tea, soft fruits and recreation in the first decades of the 1900s. The other unusual feature of TC7 was the abrupt decline in $\delta^{13}C_{org}$ and an accompanying rise in cyanobacterial pigments during the low rainfall/water drawdown period (1975–1995) implying an intensification of autochthonous dissolved organic matter (DOM) cycling with increasing microbial activity in more lentic waters, with the possibility of increasing methanogenesis/methanotrophy which can lower $\delta^{13}C_{org}$ values (Conrad et al., 2011).

Some common features across all cores suggest generalized shifts in the C balance of Tasik Chini. A decline in % LOI_{550} and a rise in sediment density occurred in all cores which, based on the SCPs, apparently dates to a common time period sometime around 1940. This suggests that forest removal around the time of World War II in the local and/or broader Pahang catchment had a measurable influence on C cycling and/or increased minerogenic influx within the entire basin. The other common feature that appears to have altered all of the sites is the weir installation and stabilization of water levels. This led to a rise in OCAR in the lotic-influenced sites (TC1 and TC7), probably due to raised water retention times which facilitated C sedimentation (Zeng et al., 2018), whereas in TC12, which was already lentic at the time of the weir installation, there was a slight decline from the previously high OCARs after water levels were raised. All three dated sites show a uniformly low C/N ratio after ca. 2000 CE indicating that lacustrine algal production became the dominant C source through declining allochthonous C influx and facilitation of algal production and sedimentation. There is a possibility that some of this C/N decline could be caused by incomplete decomposition of labile OM (Gälman et al., 2008), but the rather abrupt shifts towards lower C/N ratios after installation of the weir suggest that the water retention changes were an important contributory factor.

Synthesis

This multi-basin comparison of Tasik Chini is one of the first palaeolimnology studies in Peninsular Malaysia (see Briddon et al., 2020), and the 'whole ecosystem experiment' approach gives rare insights into tropical wetland C sedimentation. We have identified that human impacts on the lake ecosystem were detectable much earlier than the 1980s CE time horizon, when economic development accelerated in Malaysia. Instead, substantial and basin-wide shifts in C cycling began around 1940 CE and possibly a few decades earlier, reflecting the impacts of colonial development and land use changes during World War II. Since environmental and water quality monitoring is not available prior to the 1990s in Malaysia, the use of palaeolimnology in tropical data-scarce regions is helpful in detecting such baselines and tipping points of change (Walton et al., 2023). The combination of multiple proxies, archival data and historical maps helped to distinguish the relative effects of hydrological and land use change on lake ecosystem functioning and OC accumulation over long timescales. The inter-basin comparison demonstrates that localized conditions and basin morphometry strongly influence the quantity and quality of OC being buried in lake sediments, as well as the sensitivity of OCARs to human disturbances.

We have shown that modifications to lake water balance are highly consequential for OCARs, particularly in shallow flood pulse wetlands which are susceptible to water level fluctuations. Increasing the water retention time and stabilizing water levels through damming or meteorological forcing increases OC accumulation, probably due to more efficient sediment trapping and sinking (e.g. McGowan et al., 2011). Water level drawdown and dampening of flood pulse dynamics also facilitates encroachment of swamp and submerged vegetation growth, which increases OC accumulation (Mei et al., 2024), demonstrating that (disruption to) ontogenetic succession is important for C cycling (Lemke et al., 2017). In tropical regions where wetland productivity is high, such plant dynamics have the potential to be particularly influential for C accumulation. Since the installation of dams and water level controls is near ubiquitous and long-standing in human-dominated landscapes, this work emphasizes how widespread impacts on OCARs across lake districts are likely to have been changing lake C sink functions for centuries.

We also demonstrated how land use disturbances can change OC cycling in lakes by two predominant mechanisms. In 'autochthonous mode', eutrophication associated with agriculture and land development stimulates in-lake production and thereby higher OCARs, depositing OC with a lower C/N ratio (i.e. an algal signature) (Zeng et al., 2022). In 'allochthonous mode', increased OC is suppled via soil erosion when land use is intensive (Zhao et al., 2006). Both modes of operation are possible in different areas of the lake basin, illustrating the challenge of predicting how lake OCARs will respond to land use changes. Recently it has been suggested that tropical forest lakes bury more OC than their temperate counterparts due to high fluxes of terrestrially derived OC (Amora-Nogueira et al., 2022). Our results suggest that while this mechanism may have been important in the past, it previously resulted in rather low OCARs in Tasik Chini (cf. Fig. 8), probably due to the openly flooded nature at that time. Instead, the high recent sedimentary OCARs in Tasik Chini, which are now comparable to those in tropical forest lakes, have a signature more typical of phytoplankton, with labile (C- and N-rich) sediments being deposited (e.g. as seen in eutrophic and deeper temperate lakes; Keaveney et al., 2020). The long-term fate of such labile sediments is unknown since large and flat lakes are susceptible to enhanced post-depositional C decomposition (Ferland et al., 2012; Loder et al., 2023), especially in warmer conditions (Gudasz et al. 2015), and there could be implications for processes such as methanogenesis (Colina et al., 2021).

Together, our evidence suggests that, on decadal timescales, changes to land use and hydrology act in synergy to influence OCARs (Hanson et al., 2015; Zeng et al., 2018). Land use change accelerates autochthonous production and allochthonous supply of OC, while increasing water retention time through damming or changing hydroclimate improves the sedimentation of OC. Therefore, although both could be beneficial for OCARs and C burial, there are trade-offs with detriments to lake ecology, biodiversity, soil C stocks and greenhouse gas production that need to be accounted for in assessing the role of tropical wetlands as OC sinks.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Supporting information

Additional supporting information can be found in the online version of this article.

Abbreviations. CE, Common Era; DMAR, dry mass accumulation rate; HPLC, high-performance liquid chromatography; LOI, loss on ignition; LULC, land use land cover; NERC, Natural Environment Research Council; NIGFSC, NERC Isotope Geosciences Facility Steering Committee; OC, organic carbon; OCAR, organic carbon accumulation rate; OM, organic matter; PCA, principal component analysis; PDA, photodiode array; RUSLE, revised universal soil loss equation; SCP, spheroidal carbonaceous particle; Sg., Sungai (river in Bahasa); XRF, X-ray fluorescence.

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