

Holocene development and climatic sensitivity of an Amazonian peatland pole forest: Nueva York, Peru

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ARTICLE INFO

Editor: L. Sadori

Keywords:

Palaeoecology
Pollen
Carbon
Peat
Wetland
Amazonia

ABSTRACT

Extensive peat-forming wetlands are now known to occur in several parts of Amazonia, but scientific research on their properties is still in its infancy. Here, we present a new palaeoecological study of a peatland pole forest site, Nueva York, Peru. We use nineteen radiocarbon dates and pollen, geochemical, and sedimentological proxies on a 4.9 m long core spanning the last 7800 years to reconstruct the history of the site. Peat initiation occurred at c. 6200 calendar years before present (cal yr B.P.), but apparent rates of accumulation were low until c. 2300 cal yr B.P., possibly due to adverse hydroclimatic conditions and/or an episode of secondary peat decomposition, since which time some 4 m of peat has accumulated. The vegetation succession involved terrestrialization of an open water body with colonization by an open fen vegetation, followed by flooded *Mauritiella*-dominated palm swamp, mixed hardwood swamp forest, a second palm swamp (*Mauritiella*- and *Mauritia*-dominated), and finally peatland pole forest. The apparent endogenic succession was deflected on multiple occasions, suggesting that the site was affected by allogenic factors which may include river channel migration, human impact, and/or climatic events. The age-depth model strongly indicates that, unlike at other sites from the region, there is no evidence for interruption of carbon accumulation since 2300 cal yr B.P. Our new record adds to a growing body of evidence to suggest that the wetlands of western Amazonia are remarkably diverse not only in their present ecosystem properties, but also in their history and sensitivity to external forcing.

1. Introduction

In recent years it has become clear that peat soils are abundant in parts of Amazonia. Peatland mapping, however, is still an ongoing project (Hastie et al., 2024). The best-studied peat-forming region in

Amazonia is the Pastaza-Marañón Foreland Basin (PMFB) in northeast Peru, where 44,000 km² of peat-forming wetland is estimated to store about 4 (1.94–7.98) Pg of carbon, a significant amount in terms of national carbon inventories (Draper et al., 2014; Hastie et al., 2022). The high carbon density of these peatlands provides one reason to

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<https://doi.org/10.1016/j.palaeo.2026.114162>

Received 30 April 2026; Received in revised form 17 August 2026; Accepted 18 August 2026

Available online 22 August 2026

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understand the processes that drive their development and their sensitivity to past and future climatic change. The peatlands are socially, economically, and culturally important to local communities (Schulz et al., 2019). They are also important to regional biodiversity, but are threatened by human activities including resource harvesting, infrastructure development, and petroleum extraction (Roucoux et al., 2017; Lawson et al., 2022; Hergoualch et al., 2024; Lawson et al., 2026).

Palaeoecological records from PMFB peatlands are presently only available for a few sites (Roucoux et al., 2013; Lawson et al., 2014; Kelly et al., 2017; Swindles et al., 2018; Kelly et al., 2020; Sassoon et al., 2024). These studies, in combination with research on the modern ecology of the peatlands (e.g. Kalliola et al., 1991b; Junk et al., 2015; Wittmann and Householder, 2017), have shown that peatlands often form in abandoned river channels, that infill progressively: initially, with inorganic river sediments and later, through processes of hydrosereal succession, with peat (organic matter accumulating under waterlogged, anaerobic conditions; Dargie et al., 2024). The oldest basal peat date from the PMFB is from the early Holocene (8650–8990 cal yr B.P.; Läähteenoja et al., 2012) but most sites are from the late Holocene (c. 4000 cal yr B.P. to present; Lawson et al., 2026). The PMFB landscape thus can be conceptualised as a mosaic, in time and space, of related vegetation types at different stages of ecological succession (cf. Kalliola et al., 1992), with peatlands being continually created and destroyed as rivers migrate across the flat terrain.

This paper will address two knowledge gaps. Firstly, although hydrosereal succession is important in the PMFB wetlands, the pattern, timing, and drivers remain poorly understood. The modern vegetation includes a range of forms which are actively being documented, classified, and discussed by researchers (Encarnación, 1985; Kalliola et al., 1991a; Draper et al., 2018; Schulz et al., 2019; Honorio Coronado et al., 2021 and in press; Hastie et al., 2022). These forms include open vegetation (sedges, ferns); seasonally flooded forest, with mixed and variable assemblages of hardwood trees and palms; widespread, monodominant, minerotrophic *Mauritia flexuosa* palm swamp; and ombrotrophic ‘pole forest’, dominated by characteristically thin-stemmed, short-stature hardwood trees (e.g. *Pachira nitida* and *Platycarpum lorentense*) with scattered *Mauritia* palms. Local communities identify further sub-types of vegetation which have yet to be adequately accounted for by scientific classifications (Schulz et al., 2019; Honorio Coronado et al., 2023). Pollen records, generated by analysing subfossil pollen preserved in organic and mineral deposits, provide a way to understand the transitions between these vegetation types through time. Although some common patterns are emerging from the existing pollen datasets (e.g. Kelly et al., 2020), no two PMFB sites studied to date follow the same developmental trajectory. For example, some seem to be dominated by hydrosereal succession (Quistococha: Kelly et al., 2020); some appear to have been affected by past climatic episodes (San Jorge: Kelly et al., 2017; Aucayacu: Swindles et al., 2018; discussed below); and others have persisted for millennia without succeeding to closed canopy forest (Sassoon et al., 2024). More data are required to develop a reasonably comprehensive understanding of the developmental history of the PMFB wetlands.

Secondly, the sensitivity of peatlands – particularly their carbon storage function – to climatic change is a topic of key concern (e.g. Garcin et al., 2022). Two studies of PMFB peatland pole forests, San Jorge (Kelly et al., 2017) and Aucayacu (Swindles et al., 2018), showed at least one hiatus in peat accumulation within the last 2000 years that was tentatively attributed to climatic change, where a drying climate and consequently lower water table could have promoted increased decomposition of peat. The stratigraphies, however, differed substantially between the two sites and the timing of the hiatus was not synchronous (San Jorge: c. 1300–400 cal yr B.P., Aucayacu: c. 1800–1100 cal yr B.P.). Numerous records from a third site (Quistococha: Roucoux et al., 2013; Kelly et al., 2020) show no evidence for such a hiatus. Replication of these datasets is important to understand whether PMFB carbon storage has been robust in the face of past episodes of climatic

change. With climate change as the driver we would expect synchronicity between records, whereas discrepancies in timing between records would be expected if changes were driven by local changes in hydrology.

Here, we present a new multi-proxy palaeoecological record from the peatland pole forest Nueva York, Peru. We use pollen, sedimentological, and geochemical analyses to advance our understanding of peatland succession in the PMFB, an important region for carbon storage and biodiversity, and to evaluate the evidence for disruption of carbon accumulation by past climatic change.

2. Study site

The Nueva York peatland is located at 112 m elevation in the Pastaza-Marañón foreland basin (PMFB), Peruvian Amazonia, between the Tigre and Marañón Rivers (4.401°S, 74.271°W; Fig. 1). The site was named informally after a nearby village, which was established in the 1960s. The villagers use the surrounding territory, including the peatlands, to harvest resources that are central to their livelihoods, both for subsistence and for trading. A 0.5 ha permanent vegetation census plot, NYO-03, was installed at the site in 2014 as one of a network of peatlands sites administrated by the Instituto de Investigaciones de la Amazonia Peruana (Honorio Coronado and Draper, 2017) (Fig. 1-E). The site is an ombrotrophic, slightly domed peatland (Läähteenoja and Page, 2011) that today is characterized by many thin-stemmed trees (Fig. 1-C, -D) and a thick understorey of small-stemmed individuals. The tree species *Pachira nitida*, *Platycarpum lorentense*, and *Hevea guianense*, and the palm species *Mauritia flexuosa* dominate the census plot (Table 1). The vegetation structure and floristic composition indicate that the site can be classified as a ‘peatland pole forest’ (Draper et al., 2018; Honorio Coronado et al., 2021). Water table depth fluctuates throughout the year, with minimum and maximum values of –28 cm (i.e. above the surface) and 27 cm, respectively, recorded using an automated logger between December 2017 and July 2020 (Flores Llompazo et al., 2022). This water table depth range is typical for peatland pole forests in the region; other types of wetlands (palm swamps, seasonally flooded forest) usually show a greater range (Lawson et al., 2014; Flores Llompazo et al., 2022). The water table was at the surface at the time of coring. The mean annual temperature is 25 °C and mean annual precipitation is c. 3000 mm (Marengo et al., 1998; Díaz-Alván et al., 2017). Although the local climate shows little seasonality, major rivers in the PMFB exhibit an annual flood cycle with high water between February and May.

3. Materials and methods

In April 2018, a 490-cm long core (NYO-03-2018) was retrieved from Nueva York (Fig. 1-E) in 50-cm increments, with 10-cm overlaps, using a 5-cm diameter Russian-type corer (Jowsey, 1966). The core is stored under license at 4 °C at the University of St Andrews.

Radiocarbon dating was undertaken at the National Environmental Isotope Facility, Radiocarbon Laboratory, East Kilbride, UK. Nineteen samples of bulk peat were dated (volume = 3–4 cm³); sieving at 180 µm removed visible roots to minimize contamination from non-contemporaneous carbon, i.e. carbon younger than the pollen. The bulk peat was pretreated by acid-alkali-acid digestion and the remaining solids (Humin fraction) recovered and converted to graphite via Zn/Fe reduction. Radiocarbon content of sample graphite was analysed by Accelerator Mass Spectrometry (AMS) (see Ascough et al., 2024 and references therein). An age-depth model was produced using the ‘Rbacon’ package version 2.5.7 and the IntCal20 calibration curve (Blaauw and Christen, 2011; Reimer et al., 2020).

Pollen subsamples ($n = 62$, volume = 1 cm³) were treated according to standard methodology (Faegri and Iversen, 1989; Nakagawa et al., 1998; Campbell et al., 2016), spiked with exotic *Lycopodium* spores for the calculation of pollen concentrations (Stockmarr, 1971), mounted in

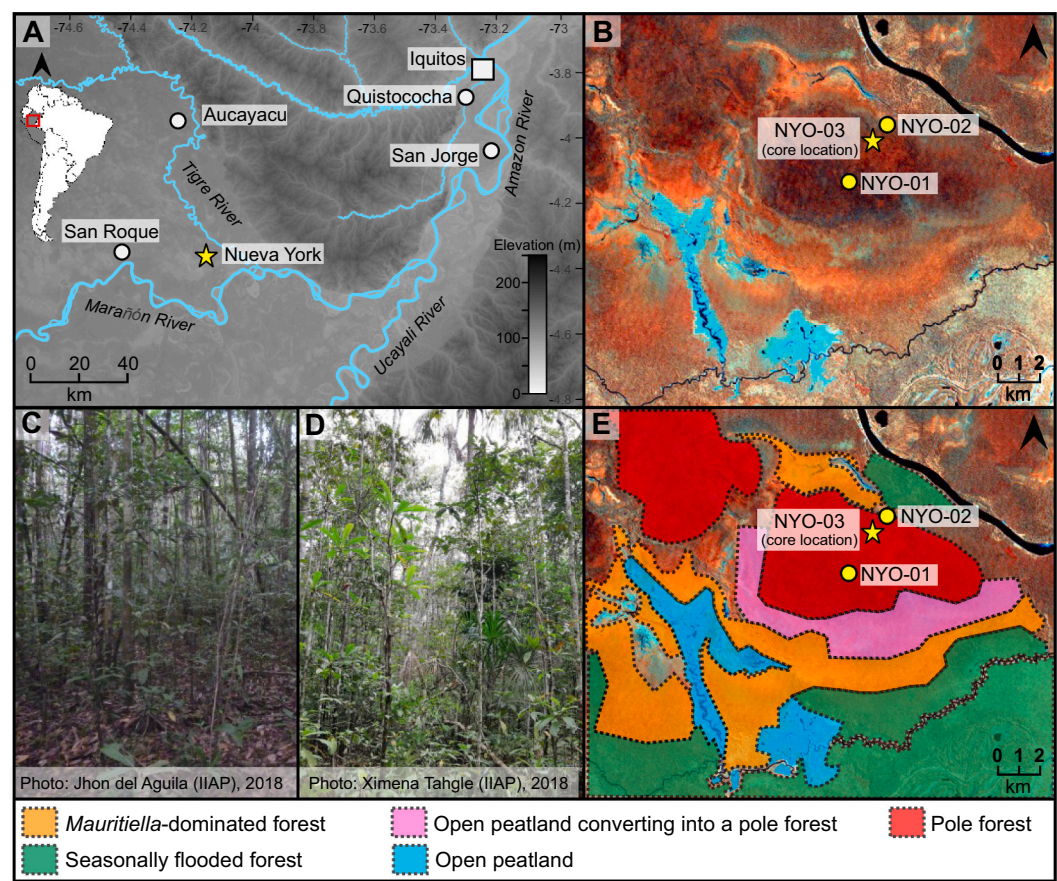


Fig. 1. Map of the study area of Nueva York, Peru. (A) Map of the northern part of the Pastaza-Marañon foreland basin (PMFB) showing the study site Nueva York (yellow star) and the peatland sites Aucayacu, San Jorge, San Roque, and Quistococha (white circles) (Roucoux et al., 2013; Kelly et al., 2017; Swindles et al., 2018; Sassoon et al., 2024). The city of Iquitos (white square) and main rivers (blue lines) are also shown. Insert map highlights Peru (grey) and the location of the PMFB (red square) in South America. (B) Landsat satellite image (false colours; band 4 = red, band 5 = green, band 7 = blue) of the areas surrounding the Nueva York peatland. Forest plots NYO-01 (yellow circle), NYO-02 (yellow circle), and NYO-03 (yellow star, core location) are also shown. (C–D) Photographs showing the pole forest vegetation present at Nueva York in 2018 (Photos: Jhon del Aguila and Ximena Tagle, IIAP). (E) Vegetation cover at Nueva York in 2018, including pole forest (red), open peatland converting into a pole forest (pink), *Mauritiella*-dominated forest (orange), seasonally flooded forest (green), and open peatland (blue). Forest plots NYO-01 (yellow circle), NYO-02 (yellow circle), and NYO-03 (yellow star, core location) are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Top twelve most abundant species at Nueva York 0.5-ha census plots NYO-01, NYO-03 (core site), and NYO-02 in order of abundance (measured as number of stems and proportion of the total number of stems >10 cm diameter at breast height, DBH) (Fig. 1–E). NYO-1 and NYO-2 were established in 2013, and NYO-03 was last re-censused in 2019. Census plots are ordered as observed along the transect from the Tigre River.

Species	Family	Number of stems			Relative abundance (%)		
		NYO-02	NYO-03	NYO-01	NYO-02	NYO-03	NYO-01
<i>Pachira nitida</i>	Malvaceae	27	102	703	5	24	80
<i>Platycarpum loretense</i>	Rubiaceae	1	79	74	0	19	8
<i>Hevea guianensis</i>	Euphorbiaceae	84	41	0	15	10	0
<i>Sagotia racemosa</i>	Euphorbiaceae	99	0	0	17	0	0
<i>Pagamea guianensis</i>	Rubiaceae	71	0	0	12	0	0
<i>Mauritia flexuosa</i>	Arecaceae	6	38	25	1	9	3
<i>Cariniana decandra</i>	Lecythidaceae	68	0	0	12	0	0
<i>Vochysia venulosa</i>	Vochysiaceae	0	0	52	0	0	6
<i>Tabebuia insignis</i>	Bignoniaceae	42	0	0	7	0	0
<i>Xylopia</i> GFL1848	Annonaceae	0	38	0	0	9	0
<i>Mouriri nigra</i>	Melastomataceae	37	0	0	6	0	0
<i>Chrysophyllum amazonicum</i>	Sapotaceae	31	0	1	5	0	0
Other species		104	119	21	18	29	2
TOTAL		570	417	876	100	100	100

silicone oil, and analysed using a Nikon Labophot-2 photomicroscope at magnifications of $\times 400$ and $\times 1000$. At least 300 pollen grains (excluding spores but including aquatic taxa) were counted in each sample. Published pollen keys (Roubik and Moreno, 1991; Colinvaux

et al., 1999), the Neotropical Pollen Database (Bush and Weng, 2007), and the reference collection at the University of St Andrews were used to identify pollen to the lowest taxonomic level possible. The size of *Mauritia* type (hereafter t.) pollen was measured to differentiate between

Table 2

Radiocarbon dates and calibrated ages for core NYO-03-2018, Nueva York, Peru.

Lab ID number	Sample Type	Depth (cm)	^{14}C age $\pm 1\sigma$	Calibrated 2σ age range (cal yr B.P.)
SUERC-101901	Bulk	31	150 $\pm$ 37	0–285
SUERC-95692	Bulk	63	315 $\pm$ 37	300–470
SUERC-101902	Bulk	100	492 $\pm$ 37	495–610
SUERC-95693	Bulk	125	596 $\pm$ 37	540–650
SUERC-101903	Bulk	160	1069 $\pm$ 35	925–1060
SUERC-101907	Bulk	206	1054 $\pm$ 35	910–1050
SUERC-101908	Bulk	232	1303 $\pm$ 37	1140–1290
SUERC-95694	Bulk	254	1540 $\pm$ 37	1350–1520
SUERC-101910	Bulk	287	1648 $\pm$ 37	1420–1680
SUERC-95698	Bulk	326	1715 $\pm$ 37	1540–1700
SUERC-101911	Bulk	350	1896 $\pm$ 37	1720–1910
*SUERC-101912	Bulk	371	1502 $\pm$ 35	1310–1500
SUERC-101913	Bulk	395	2271 $\pm$ 35	2160–2340
SUERC-95699	Bulk	415	3383 $\pm$ 37	3500–3760
SUERC-101917	Bulk	430	4522 $\pm$ 37	4990–5310
SUERC-101918	Bulk	440	4911 $\pm$ 35	5590–5720
SUERC-84545	Bulk	453	5339 $\pm$ 38	6010–6270
SUERC-101919	Bulk	470	6035 $\pm$ 37	6770–6980
SUERC-101920	Bulk	486	6893 $\pm$ 38	7640–7830

* Outlier, possibly due to contamination.

Mauritia flexuosa (typically $>40\ \mu\text{m}$ diameter) and *Mauritiella armata*, which is typically smaller (Colinvaux et al., 1999; Kelly, 2015; Kelly et al., 2017). Microscopic charcoal fragments were quantified by scanning the pollen samples until at least 50 *Lycopodium* spores had been counted using a Nikon Labophot-2 photomicroscope at a magnification of $\times 400$ (Whitlock and Larsen, 2002).

A CONISS constrained hierarchical clustering analysis and a broken stick model were performed using the ‘vegan’ package version 2.5.7 (Oksanen et al., 2013) in R version 4.1.2 (R Development Core Team, 2022) to aid in the zonation of the pollen diagram. A Detrended Correspondence Analysis (DCA) (Hill, 1979) was performed on pollen percentage data to identify the main axes of variability using the ‘vegan’ package. Pollen taxa occurring in five or more samples (Birks and Gordon, 1985) were used in the ordination, reducing the matrix to 88 morphotypes. For the DCA, *Mauritia* t. was split into two subgroups: *Mauritia* ($>40\ \mu\text{m}$ diameter) and *Mauritiella* ($<40\ \mu\text{m}$ diameter).

Dry bulk density (DBD) was measured on samples ($n = 61$; volume = $1\ \text{cm}^3$) dried at $105\ ^\circ\text{C}$ for 12 h. Loss-on-ignition ($n = 66$; volume = $1\ \text{cm}^3$) was measured on samples ignited at $550\ ^\circ\text{C}$ for 4 h (Heiri et al., 2001) to find the proportion of organic matter (OM). Magnetic susceptibility (MS) was measured using a Bartington MS2 meter and MS2G probe at 2-cm intervals. Samples for total carbon and nitrogen ($n = 62$; volume = 5 mg) were dried at $40\ ^\circ\text{C}$, milled, weighed into tin caps, and analysed using an Elementar vario EL Cube analyser at $950\ ^\circ\text{C}$ (Pella, 1990).

Leaf-wax n-alkanes were extracted from a teaspoon amount of freeze-dried samples using an accelerated solvent extractor (ASE-300, Thermo-Dionex) with a dichloromethane:methanol (9:1, v/v) solvent mixture. The apolar lipid fraction was separated from the total lipid extract by aluminium oxide column chromatography, eluting with hexane:dichloromethane (9:1, v/v). The purified n-alkane fraction was checked for purity and peak identification by gas chromatography mass spectrometry (GC/MS) prior to isotope analysis.

Compound-specific hydrogen isotope ratios (expressed as δD) of individual n-alkanes were determined using a Thermo Trace 1310 GC coupled via a GC IsoLink II to a Thermo Delta V Plus isotope-ratio mass spectrometer (IRMS) to understand past moisture conditions. The high-temperature pyrolysis reactor was operated at $1420\ ^\circ\text{C}$. The H_3^+ factor was determined daily and monitored for stability throughout the analytical sequence. An n-alkane standard mixture was analysed in triplicate for normalisation and quality control. Each sample was also analysed in triplicate, and the individual $\delta^2\text{H}$ values were calculated from the mean of replicate injections.

The vegetation survey was carried out in 0.5 ha forest plots following

RAINFOR protocols (Malhi et al., 2002). All stems $>10\ \text{cm}$ at diameter breast height (DBH) were tagged, identified, and counted. DBH, height, and location in the plot for the $>10\ \text{cm}$ stems were recorded.

4. Results

The 490-cm core consisted of peat (0–454 cm, defined as $>65\%$ OM; cf. Hastie et al., 2022) overlying organic-rich clay (454–490 cm, c. 11–53% OM). An age-depth model was developed using all nineteen ^{14}C dates (although one, SUERC-101912, appears to be out of sequence), indicating a basal age of c. 7810 cal yr B.P. (calendar years before 1950 CE) and peat initiation c. 6175 cal yr B.P. (Table 2, Fig. 2). Modelled accumulation rates were 0.83–2.5 mm/year (0–399 cm; all peat) and 0.085–0.42 mm/year (400–450 cm, peat; 450–490 cm, clay). The c. 8-cm pollen sampling interval represents 30–94 years between 0 and 399 cm and 74–854 years between 400 and 490 cm.

The pollen record included 150 pollen morphotypes (including 30 unknown morphotypes), of which only 22 ever exceed 5%, and 32 occur in fewer than five samples. The most abundant taxa are shown in Fig. 3 (Supplementary Material Fig. S-1). Pollen concentrations were 4943–281,064 grains cm^{-3} and pollen preservation was good, with few indeterminate grains $<10\%$ (mean: 1.89%). The uppermost sample is at 10 cm depth down-core due to poor retrieval of the wet surface peat. Six statistically significant pollen assemblage zones were identified and are described below (Supplementary Material Figs. S-2–S-3). Subzones were placed by eye to assist with description of variation within zones.

4.1. Zone 1 (490–428 cm; 7810–4965 cal yr B.P.)

Zone 1 has three distinct subzones (Fig. 3). Subzone 1a (490–484 cm) is characterized by abundant *Mauritia* t. pollen (35%; most grains $<40\ \mu\text{m}$ diameter) and smaller amounts of Combretaceae/Melastomataceae (10–12%), Cyperaceae (8%), *Symmeria paniculata* (3–5%), Myrtaceae (2–5%), and *Ilex* sp. (2–5%). In Subzone 1b (484–470 cm), these taxa are largely replaced by *Cecropia* sp. (36–54%) and Cyperaceae (17–20%), accompanied by smaller amounts of Poaceae (4%), Asteraceae (1–4%), Piperaceae (1–4%), *Ficus* (1–3%), Amaranthaceae (0–3%), and Moraceae/Urticaceae (2%). In Subzone 1c (470–428 cm), *Mauritia* t. (grains $<40\ \mu\text{m}$ diameter) shows a second expansion (13–77%), accompanied by Combretaceae/Melastomataceae (6–16%), Myrtaceae (2–9%), *Symmeria* (2–5%), *Ilex* (0–3%), and *Alchornea* (0–3%).

Subzones 1a and 1c plot in the centre of the DCA biplot (closer to zero on both axes; Fig. 4), reflecting the abundance of *Mauritia* t. Subzone 1b samples, which have the most positive values of this zone on

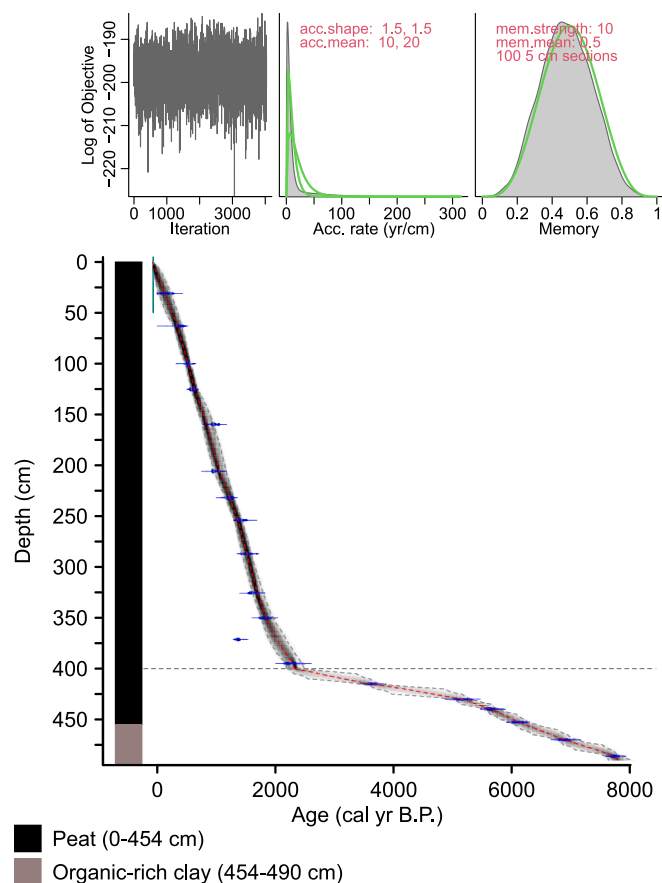


Fig. 2. The age-depth model of the peat and sediments from core NYO-03-2018, Nueva York, Peru. The lithology of the core shows peat (black) and organic-rich clay (brown). The Markov Chain Monte Carlo iterations, prior (green curve) and posterior (grey histogram) distributions for the accumulation rate, and the memory of the Bayesian age-depth model are also shown. The dashed line indicates an inflection point in the curve at 399 cm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

both axes, plot in the positive half of both axis 1 and 2 in the DCA biplot, reflecting the abundance of Cyperaceae, Poaceae, Piperaceae, and *Cecropia*.

Charcoal fragments, mostly <40 μm in size, are present throughout Zone 1; Subzone 1c has the highest charcoal abundance of the whole record (80 fragments) (Fig. 5). The organic content increases through the zone, from 11% at the beginning of the record to >80% in Subzone 1c (above 470 cm), first exceeding 65% at 454 cm, which thus marks the transition from clay to peat. Carbon (4.4–50.9%), nitrogen (0.38–1.1%), and C/N ratio (11.4–48.0) similarly increase through the zone. MS is low, between -1 and 0 , and DBD decreases through the zone from 0.16 to 0.10 g/cm^3 . δD C27 and δD C29 decrease throughout the zone, where δD C27 has values between -169.62 and -137.29 and δD C29 has values between -163.29 and -126.29 .

4.2. Zone 2 (428–308 cm; 4965–1610 cal yr B.P.)

This zone is characterized by lower abundance of *Mauritia* t. than the subzone below with most grains <40 μm diameter, and higher percentages of *Symmeria* and Myrtaceae (Fig. 3). The zone has three distinctive sections: Subzone 2a (428–388 cm) has low *Mauritia* t. (1–11%) and high Combretaceae/Melastomataceae (5–23%), Myrtaceae (8–18%), *Ilex* (2–15%), *Pera* (4–12%), and Boraginaceae type 1 (0–12%); Subzone 2b (388–364 cm) sees a small increase in *Mauritia* t. (6–15%) and Cyperaceae (3–6%) and a more substantial increase in

Symmeria (24–57%); and Subzone 2c (364–308 cm) is characterized by a further reduction in *Mauritia* t. (0–1%, except for a single-sample peak of 56% at 312 cm) which is replaced by *Symmeria* (14–60%), Myrtaceae (1–43%), Boraginaceae type 1 (1–35%), *Ilex* (0–9%), and Poaceae (0–11%). The samples clustered towards the positive end of DCA axis 1 and at the negative end of DCA axis 2 (Fig. 4) reflecting high percentages of *Symmeria*, Myrtaceae, *Sapium*, and Boraginaceae type 1 and low percentages of *Mauritia* t., Cyperaceae, and Poaceae.

Charcoal fragments are present throughout the zone, reaching 49 fragments in subzone 2a but decrease thereafter to <10 fragments (Fig. 5). Carbon (35.0–50.1%) and nitrogen (0.84–1.76%) increase slightly throughout, while the C/N ratio decreases (59.7–24.5). MS remains low and DBD decreases through the zone from 0.13 to 0.04 g/cm^3 . δD C27 fluctuates between -181.95 to -99.95 . δD C29 initially increases in the zone from -175.62 but thereafter remains stable between -156.62 and -142.62 .

4.3. Zone 3 (308–252 cm; 1610–1360 cal yr B.P.)

Herbaceous taxa increased in this zone (Fig. 3). Subzone 3a (308–268 cm) sees expansions of Cyperaceae (7–77%), Poaceae (2–29%), *Mauritia* t. (3–29%; with most grains <40 μm diameter), and Asteraceae (0–3%) at the expense of *Symmeria* (2–3%) and Myrtaceae (0–7%). In Subzone 3b (268–252 cm) the herbaceous elements decrease once more to low values, and *Mauritia* t. (50–53%), Myrtaceae (12–13%), *Symmeria* (3%), Combretaceae/Melastomataceae (2–3%), and *Ilex* (2%) increase. The samples in Zone 3 plot towards the positive ends of DCA axes 1 and 2 (Fig. 4), with a shift towards the centre of the plot in the upper part of the zone, reflecting the abundance of open herbaceous taxa in the lower part of the zone, and the increase in arboreal taxa at the top.

Charcoal fragments become scarce in this zone (<10 fragments) and remain so for the rest of the sequence (Fig. 5). Carbon (37.3–52.9%), nitrogen (1.46–2.22%), and C/N ratio (18.1–36.3) oscillate throughout the zone, the latter typically at lower values than in Zone 2. MS (-1.67 – 0.33) and DBD (0.06 – 0.08 g/cm^3) remain low throughout the sequence, except for an initial increase in DBD to 1.3 g/cm^3 . δD C27 decreases in zone 3 to between -152.95 and -114.62 , whereas δD C29 fluctuates between -151.29 and -133.95 .

4.4. Zone 4 (252–148 cm; 1360–770 cal yr B.P.)

Zone 4 is characterized by the increase of *Mauritia* t. with grains <40 μm diameter (58–91%), which is consistently above 80% in Subzone 4a (252–188 cm) where it is accompanied by small amounts of Combretaceae-Melastomataceae (0–2%), Myrtaceae (1–4%), *Cecropia* (0–2%), Poaceae (0–2%), and *Alchornea* (0–2%) (Fig. 3). In Subzone 4b (188–148 cm) *Mauritia* t. values fall slightly (58–68%) and *Symmeria* (0–16%), Myrtaceae (2–5%), *Ilex* (2–5%), and *Alchornea* (2–5%) increase. In the DCA biplot, the samples plot at the negative end of axis 1 and to the centre of axis 2, reflecting the abundance of *Mauritia*, *Mauritiella*, and *Alchornea* (Fig. 4).

Carbon (37.2–49.2%), nitrogen (1.06–2.76%), and C/N ratio (14.8–46.4) fluctuate throughout the zone (Fig. 5). MS and DBD values show little change. δD C27 decreases throughout the zone, from -154.29 to -117.29 , whereas δD C29 remains stable around -154.62 to -147.95 .

4.5. Zone 5 (148–60 cm; 770–320 cal yr B.P.)

In Zone 5, *Mauritia* t. decreases in abundance relative to the zone below to 20–52% (Fig. 3). The mean diameter of *Mauritia* t. grains increases to >40 μm for the first time in this record. *Alchornea* (2–28%) increases substantially, along with lesser increases in Malvaceae (0–19%), *Lueheopsis* (1–13%), Poaceae (0–7%), Moraceae/Urticaceae (0–5%), *Virola/Iryanthera* (0–4%), *Tabebuia* (0–3%), *Platycarpum*

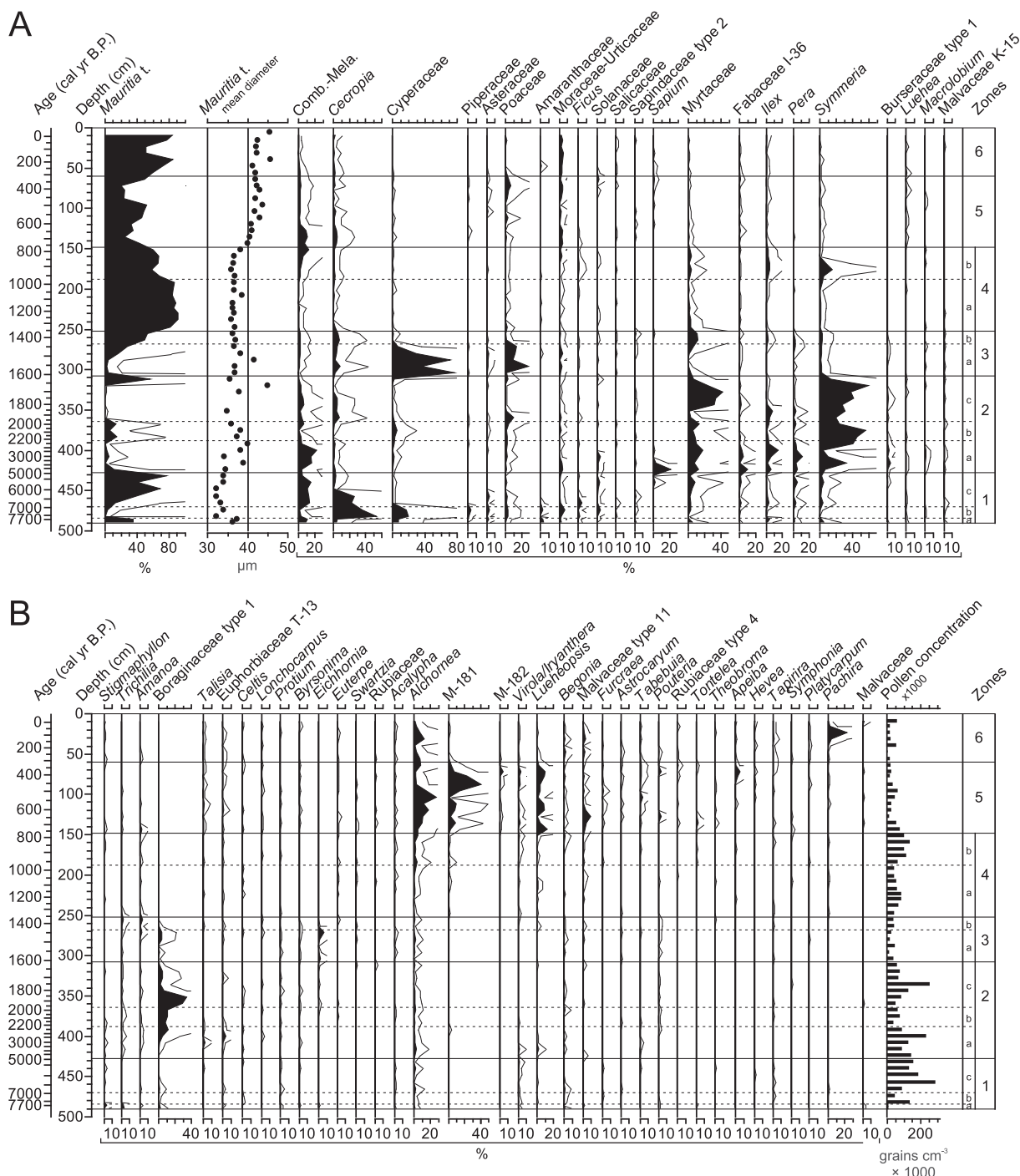


Fig. 3. Fossil pollen from core NYO-03-2018, Nueva York, Peru. Data are plotted against depth (cm), with age (cal yr B.P.) as a secondary y-axis, showing the most abundant taxa (%; Supplementary Material Fig. S-1 shows a complete pollen diagram) and pollen concentration (grains cm⁻³) from the record. The taxa are plotted in the order in which they appeared in the record. *Mauritia t.* pollen grain mean diameter (μm) is also shown. Comb.-Mela. abbreviates Combretaceae-Melastomataceae.

(0–3%), Asteraceae (0–1.5%), *Euterpe* (0–1%), *Symphonia* (0–1%), *Tapirira* (0–1%), *Begonia* (0–1%), and *Pachira* (0–1%). The samples plot towards the negative end of DCA biplot axis 1 and towards the positive end of axis 2 (Fig. 4), reflecting the appearance of *Apeiba*, *Virola/Iryanthera*, *Lueheopsis*, *Tabebuia*, *Tapirira*, *Alchornea*, *Hevea*, and *Platycarpum* in the record.

Carbon (33.2–56.7%), nitrogen (1.33–2.84%), and C/N ratio (14.8–42.7) fluctuate similarly to the previous two zones. DBD continues to be low (0.051–0.082 g/cm³), but MS shows a substantial peak, reaching 5.67 at 126 cm, which is substantially higher than at any other point in the record (Fig. 5). δD C27 declines slightly throughout the

zone, with values between –161.95 and –141.29. δD C29 shows little change, with values between –146.62 and –138.62.

4.6. Zone 6 (60–0 cm; 320 cal yr B.P. to modern)

Mauritia t. (49–85%; mean grain size diameter > 40 μm) increases in abundance again in Zone 6 (Fig. 3). *Alchornea* (2–13%), *Malvaceae* (0–8%), *Tapirira* (0–2%), *Hevea* (0–1%), *Begonia* (0–3%), *Platycarpum* (0–1%), and *Ilex* (0–1%) have similar abundances as the previous zone, while *Lueheopsis* decreases in abundance to <3%. Above 30 cm, *Pachira* increases in abundance to 24%. In the DCA biplot (Fig. 4), the samples

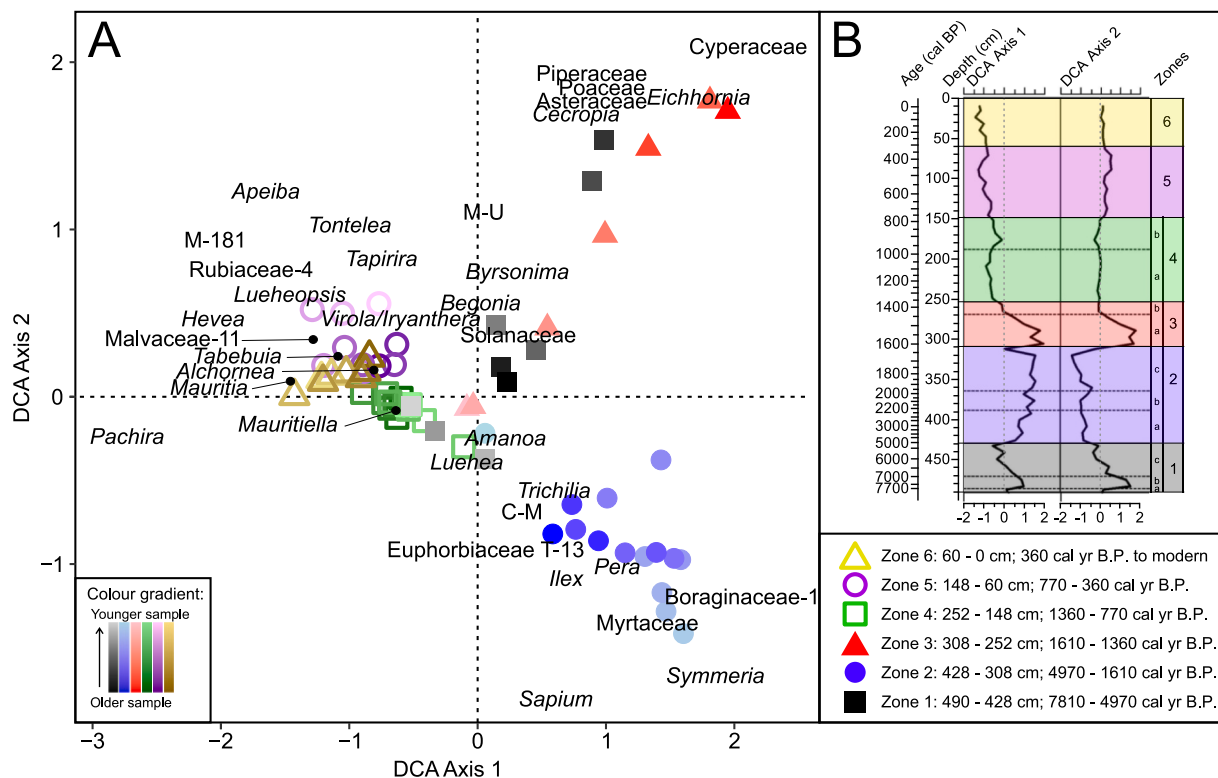


Fig. 4. Biplot of the Detrended Correspondence Analysis (DCA) of the pollen from core NYO-03-2018, Nueva York, Peru. Axes 1 and 2 have eigenvalues of 0.5679 and 0.3314, respectively. Samples and species scores are shown on the left (A) and sample scores are shown on the right (B). Samples are separated in six pollen zones: zone 1 (7810–4970 cal yr B.P.; black closed squares), zone 2 (4970–1610 cal yr B.P.; blue closed circles), zone 3 (1610–1360 cal yr B.P.; red closed triangles), zone 4 (1360–770 cal yr B.P.; green open squares), zone 5 (770–320 cal yr B.P.; purple open circles), and zone 6 (320 cal yr B.P. to modern; yellow open triangles). M-U. abbreviates Moraceae-Urticaceae and C-M abbreviates Combretaceae-Melastomataceae. *Mauritia* t. pollen were split into two subgroups (*Mauritia*, >40 μ m diameter; *Mauritiella*, <40 μ m diameter). A colour gradient from darker to lighter shows the oldest to youngest sample in each zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

plot towards the negative end of axis 1 and close to zero on axis 2, reflecting the abundances of *Mauritia* and *Pachira*.

Carbon (39.2–55.8%), nitrogen (0.97–2.15%), and C/N ratio (21.5–54.5) fluctuate similarly to the preceding three zones. MS values are low (–3.67 to –1), and DBD (0.063–0.10 g/cm³) increases slightly through the zone (Fig. 5). δ D C27 increases in the beginning of the zone, from –164.29, to thereafter have stable values around –144.29 to –133.95. δ D C29 shows little variation from previous zone, fluctuating between –141.62 and –129.62.

5. Palaeoenvironmental interpretation and discussion

The c. 7800-year long Nueva York record, with peat formation starting c. 6300 cal yr B.P., is the second oldest after Aucayacu (both records are located along the Tigre River, Fig. 1-A) (Lähteenoja et al., 2012; Swindles et al., 2018) and among the best-resolved palaeoecological records available from the PMFB. Here, we interpret the record in chronological sequence, reconstructing the changing palaeoenvironment using the available data. We make comparisons with other records from the region, focusing on filling the knowledge gaps around vegetation succession and sensitivity to climate change.

5.1. Early site development (7800–6900 cal yr B.P.; Subzones 1a and 1b)

Like many other studied PMFB peatlands (Roucoux et al., 2013; Lawson et al., 2014; Kelly et al., 2017; Swindles et al., 2018), the characteristics of the sedimentological and geochemical data at the beginning of our record, c. 7800 cal yr B.P., are consistent with the site having originated by river meandering cutting off a channel, forming an

oxbow lake (Fig. 5). Influence from a main river channel must have declined significantly, as coarser sediment grains (i.e. silt and sand) previously reported by Lähteenoja et al. (2012) were absent from our core. The low C/N value at the base is consistent with the organic material being dominantly algal in origin, like values reported from times of lake conditions at Quistococha (Meyers, 1994; Lawson et al., 2014; Kelly et al., 2018).

In the lowermost samples (Subzone 1a), high values of *Mauritia* t. (36 μ m mean grain size, probably representing *Mauritiella armata*) and Combretaceae-Melastomataceae, together with arboreal taxa typical of some forms of floodplain vegetation (*Symmeria*, Myrtaceae, and *Ilex*) and herbaceous Cyperaceae, suggest that the site was quite deeply flooded (*Mauritiella armata* tolerates flooding up to 3–4 m) (Nicholson, 1997; Pennington et al., 2004). A similarly short-lived peak in *Mauritiella* and Combretaceae-Melastomataceae, interpreted to represent a herbaceous fen with scattered palms and deeper flood levels, was observed in the early parts of San Jorge at c. 2100 cal yr B.P. (Kelly et al., 2017).

Throughout the first 1500 years of the record (Subzones 1a–1b), OM concentration and C/N steadily increase, indicating a gradual infilling and shallowing of the lake with a gradual shift in the organic source material from algae to vascular plants (Fig. 5). Herbaceous taxa increase after 7600 cal yr B.P. (Subzone 1b), suggesting colonization by herbaceous or shrubby vegetation of the margins of the lake and/or shallow areas (Kalliola et al., 1991a; Kelly et al., 2017). The high input of pollen from the pioneer tree *Cecropia* sp. (30–50%) after 7500 cal yr B.P. suggests that this genus was likely growing locally (in open areas such as canopy gaps or along river margins). *Cecropia* pollen abundances typically do not exceed 15–20% unless locally present (Bush and Colinvaux, 1988; Bush and Rivera, 1998; Bush and Rivera, 2001). Two other taxa,

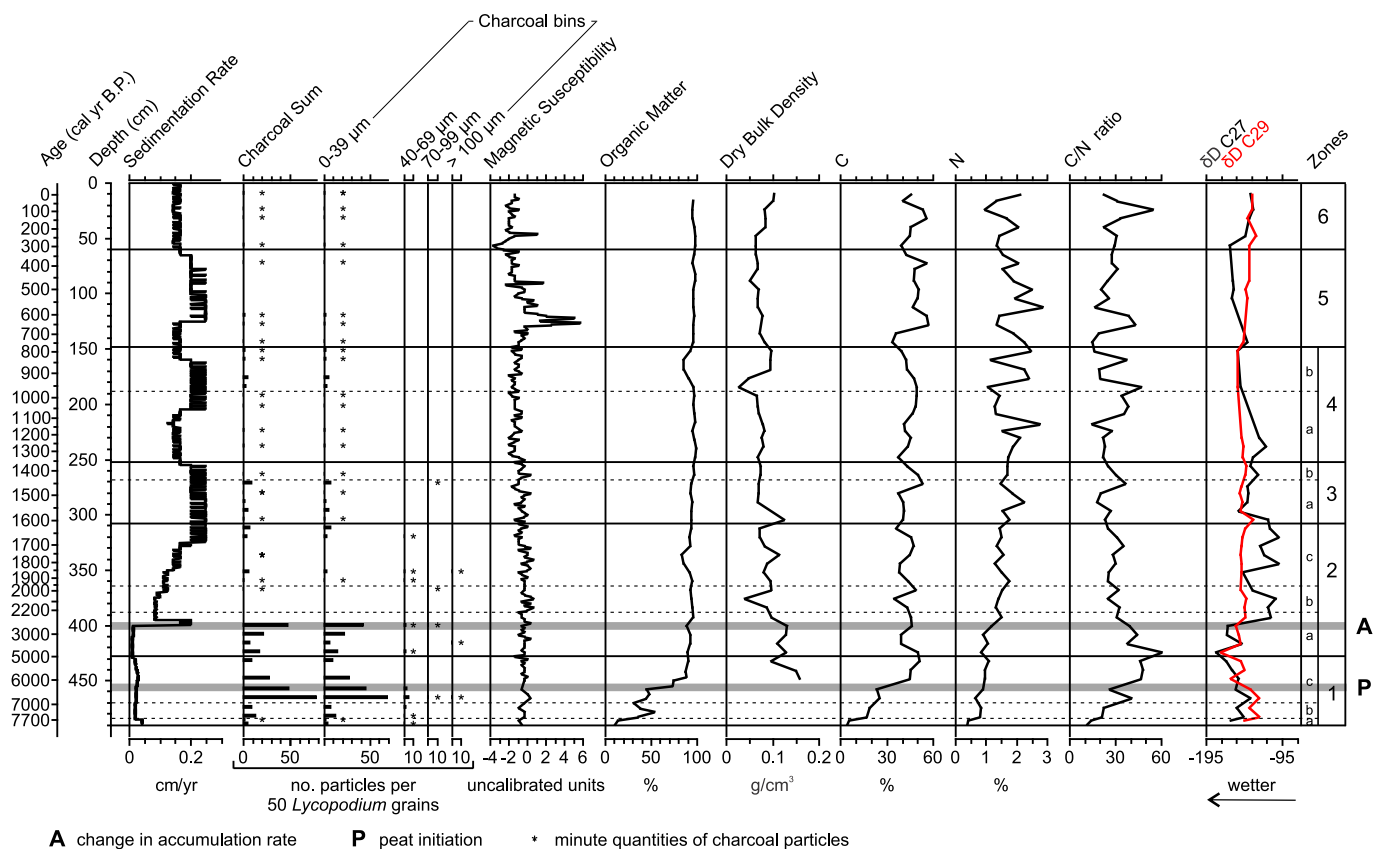


Fig. 5. Diagram from core NYO-03-2018, Nueva York, Peru, showing sedimentation rate (cm/yr), charcoal sum with size bins (no. of particles per 50 *Lycopodium* grains), magnetic susceptibility, (uncalibrated units), organic matter (%), dry bulk density (g/cm^3), carbon (C; %), nitrogen (N; %), C/N ratio, and δD C27 (black line) and δD C29 (red line) plotted against depth (cm) with age as secondary y-axis (cal yr B.P.). P abbreviates peat initiation and A abbreviates accumulation change. Asterisks (*) denotes minute quantities of charcoal particles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Salicaceae and *Alchornea*, increased after 6900 cal yr B.P.; like *Cecropia*, they represent fast-growing species that colonize disturbed ground.

The prolonged dominance of short-lived arboreal and herbaceous plants c. 7500–6900 cal yr B.P. (Subzone 1b) suggests that the area was exposed to continued disturbance, possibly irregular deep flooding, that hindered succession to closed-canopy forest. A similarly slow site development was seen at San Jorge, where *Cecropia* and Cyperaceae dominated for about 1600 years before a palm swamp formed (Kelly et al., 2017). In the absence of disturbance, we would expect that the dominant tree taxa *Cecropia*, Salicaceae, and *Alchornea* (Worbes et al., 1992; Myster, 2017) would gradually be outcompeted by longer-lived and more shade-tolerant trees, as seen at Quistococha where the Cyperaceae phase only lasted c. 100 years before a palm swamp developed (Roucoux et al., 2013).

Notably, the Cyperaceae-dominated phase at Nueva York is not associated with peat formation, unlike at Quistococha and San Jorge (Roucoux et al., 2013; Kelly et al., 2017). Continued clay input from flooding by sediment-laden river water, coupled with partial oxidation of the sediments by biological or wave-induced mixing in a shallow open-water setting, may be inferred from the absence of peat during this interval in our core. Though peat had not started to form at the core site itself in this interval, it is possible that it was accumulating in the surrounding area.

5.2. Peat initiation and the early peat swamp forest (6900–2200 cal yr B.P.; Subzones 1c and 2a)

The gradual transition to peat at Nueva York coincided with the replacement of Cyperaceae-dominated open vegetation by a less diverse *Mauritiella*-dominated swamp forest. Peat initiation was likely caused by a combination of mechanisms including infilling of the basin and/or a decrease in the maximum depth of flooding, allowing establishment of *Mauritiella* and other trees. From the presence of peat after 6200 cal yr B.P. we can infer that the site was generally waterlogged, with low oxygen and nutrient conditions allowing plant litter to accumulate. The apparent rate of peat accumulation, however, is very low by comparison with both the upper part of this core, and with other PMFB sites; here, c. 4000 years are represented by just 55 cm of material. The peat returned high C/N values suggesting that much labile material (e.g. cellulose) has been lost, leaving more recalcitrant, structural material (e.g. lignin). At San Jorge and Aucayacu (Kelly et al., 2017; Swindles et al., 2018), clear hiatuses were interpreted as evidence of climatic events driving either decreased plant litter production (increased climatic wetness) or increased OM mineralization (increased drought). A similar hiatus appears to be a consistent feature of peatlands in the Congo Basin (Garcin et al., 2022). The age-depth model at Nueva York does not indicate a step-change unequivocally indicating a discrete peat decomposition event (cf. Garcin et al., 2022) and could equally result from persistent

low apparent rates of accumulation. It is possible that for much of its early history, the site was always close to a tipping point between net peat accumulation and decomposition.

Charcoal fragments were found in the record until c. 2330 cal yr B.P., most likely representing anthropogenic fire. Findings of charcoal in Amazonian palaeoecological records have repeatedly been linked to humans with natural fires almost non-existent due to the wet conditions of the forests (e.g. [Nepstad et al., 2004](#); [Aragão et al., 2007](#); [Bush et al., 2007](#); [McMichael et al., 2012](#); [Bush et al., 2016](#); [Kelly et al., 2018](#); [Åkesson et al., 2023](#)). The small charcoal fragment size (<40 µm), as well as the openness of the canopy, suggests long-distance transport and a more regional signal. A small number of larger fragments (40–115 µm) where, however, recorded indicating the possibility of a more localized fire signal. Archaeological sites have been reported throughout the PMFB, and though most sites to date remain undated archaeological evidence near Quistococha show human occupation around 2690–2350 cal yr B.P. ([Rivas Panduro, 2006](#); [Rivas et al., 2006](#); [Kelly et al., 2018](#); [Coomes et al., 2021](#)).

Although the record is relatively compressed before 2200 cal yr B.P., compared with the later part of the record, it is clear that by c. 5000 cal yr B.P. the *Mauritiella* swamp had given way to a community containing many taxa commonly found in swamps with hardwood trees and/or shrubs, e.g. *Symmeria*, Myrtaceae, *Alchornea*, Fabaceae, Combretaceae-Melastomataceae, *Sapium*, *Pera*, and *Ilex* ([Pennington et al., 2004](#)).

The gradual increase in these taxa throughout the *Mauritiella* palm phase suggests endogenic successional turnover ([Kvist and Nebel, 2001](#)). A similar pattern of change occurred at Quistococha several thousand years later, supporting the interpretation that the pattern lake – Cyperaceae – *Mauritiella* – *Symmeria*/Myrtaceae is a common one in endogenic ecological succession in the region ([Roucoux et al., 2013](#)).

5.3. Rapid apparent peat accumulation after 2300 cal yr B.P. (Subzone 2b and 2c)

The large increase in the apparent rate of peat accumulation at 399 cm (2300 cal yr B.P.) marks a step change in the history of the site as a peatland. Although the apparent rate of peat accumulation is not a simple index of the carbon accumulation history of a peatland site ([Young et al., 2021](#)), the well-resolved age-depth model of Nueva York indicates rapid and apparently uninterrupted peat accumulation after 2300 cal yr B.P. There is little obvious change to the palynological assemblages during this transition, which continue to indicate *Symmeria*/Myrtaceae forest, although repeated oscillations in the relative abundance of the taxa *Symmeria*, Myrtaceae, *Ilex*, Boraginaceae type 1, *Mauritia* t., and Cyperaceae suggest variability in flooding depth (and/or frequency) and perhaps also in nutrient supply. A notable decrease in microscopic charcoal particle abundance in Subzone 2b indicates at most infrequent local burning and is also consistent with a reduction in

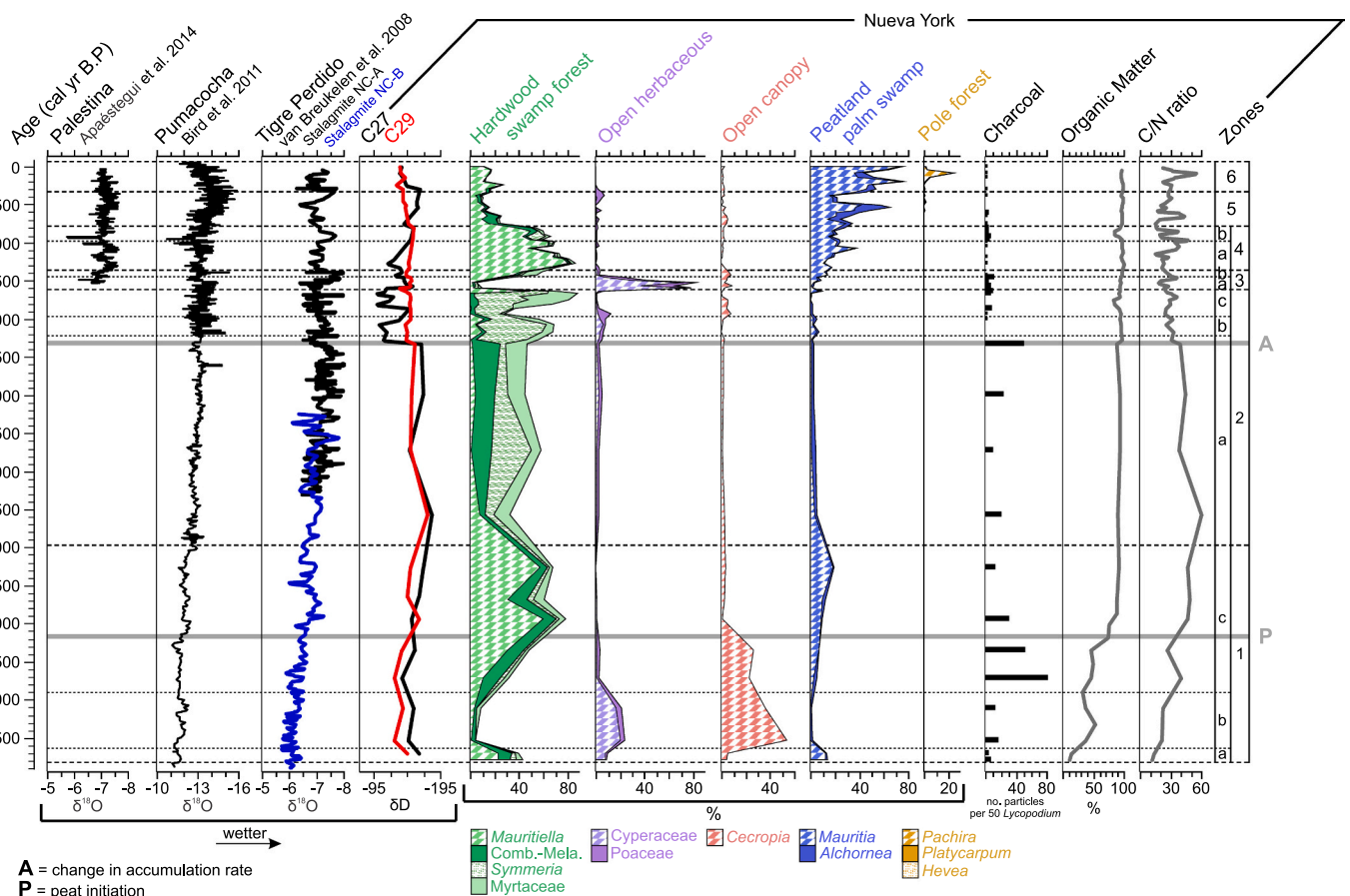


Fig. 6. Diagram showing the climate records from Palestina cave ($\delta^{18}\text{O}$; [Apaéstegui et al. \(2014\)](#)), Lake Pumacocha ($\delta^{18}\text{O}$; [Bird et al. \(2011\)](#)), and Tigre Perdido cave ($\delta^{18}\text{O}$; [van Breukelen et al. \(2008\)](#)) plotted against age (cal yr B.P.). Selected data from Nueva York, Peru, is also shown, including: δD C27 (black line) and δD C29 (red line), selected pollen taxa (%), charcoal (no. of particles per 50 *Lycopodium* grains), organic matter (%), and C/N ratio. Selected pollen are grouped in summed ecosystem groups, including hardwood swamp forest (green; *Mauritiella*, Comb.-Mela., *Symmeria*, and Myrtaceae), open herbaceous (purple; Cyperaceae and Poaceae), open canopy (red; *Cecropia*), peatland palm swamp (blue; *Mauritia* and *Alchornea*), and pole forest (yellow; *Pachira*, *Platycarpum*, and *Hevea*). A abbreviates accumulation change, P abbreviates peat initiation, and Comb.-Mela. abbreviates Combretaceae-Melastomataceae. *Mauritia* denotes *Mauritia* t. pollen >40 µm diameter and *Mauritiella* denotes *Mauritia* t. pollen <40 µm diameter. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

inputs of far-travelled pollen (and charcoal) under a closed canopy (Jacobsen and Bradshaw, 1981).

Perhaps more significantly, the change to a steeper age-depth curve at 2300 cal yr B.P. coincides with a substantial but short-lived shift to isotopically lighter C27 alkanes, which may indicate that the climate became drier (Fig. 6). A shift to a drier climate could in principle be consistent with a scenario like that hypothesized by Garcin et al. (2022), whereby an interval of drought would have led to a fall in the water table and oxidation leading to secondary decomposition of peat (399–454 cm; discussed in Section 5.2), which itself carries an isotopic signature of the wetter climate in which it formed; thus the increase in apparent peat accumulation rate at 399 cm could be understood as the recovery of the peatland to ‘normal’ conditions following a drought event that mineralized much of the pre-existing peat. However, there are substantial discrepancies between the δD climate proxies for C27 and C29, which suggest that in this record, changes in moisture source are not the only (perhaps not even the dominant) control on the δD signal. Given the extent of past vegetation change at Nueva York, plant type effects (e.g. differential fractionation for C3 and C4 plants, or for mono- and dicotyledons) are likely to be important (Liu et al., 2022). Fractionation due to evapotranspiration (Kahmen et al., 2013) may also vary from one vegetation type to another. More research is needed to understand how to interpret the δD record in PMFB peatland ecosystems, e.g. by measuring isotopic signatures in litter samples from different present-day vegetation types and developing a method to correct for these effects in the palaeoenvironmental record (using pollen data or other approaches: Santos et al., 2026).

In the absence of a reliable in situ palaeoclimatic record, we can instead examine independent palaeoclimatic datasets from the region. However, these datasets offer little support for the suggestion that the change to a steeper age-depth curve at 2300 cal yr B.P. was driven by climatic change. A Holocene stable isotope record from a speleothem from Tigre Perdido in the Andean foothills on the western edge of the PMFB, 400 km WSW of Nueva York (van Breukelen et al., 2008), indicates that regional climate became steadily wetter c. 10,000–3000 cal yr B.P., and has remained wet (though variable) ever since, but the resolution of this record is insufficient to rule out a short-lived drought event (Fig. 6). The better-resolved Lake Pumacocha record of Bird et al. (2011), in the eastern Andes 800 km SW of Nueva York, shows no significant climatic change during this interval.

After 2300 cal yr B.P. (399 cm), the apparent peat accumulation at Nueva York (c. 4 m) far exceeds that of the PMFB pole forest peatland sites San Jorge (c. 2.5 m; Kelly et al., 2017) and Aucayacu (c. 60 cm; Swindles et al., 2018). The Nueva York age-depth curve shows no evidence of hiatuses, unlike both San Jorge (probable hiatus between c. 1300 and 400 cal yr B.P.) and Aucayacu (probable hiatus after 2500 to at least 700 cal yr B.P.). The records from San Jorge and Aucayacu have been interpreted as showing pronounced shifts in the rate of peat accumulation, possibly due to regional climate change, but the pattern and timing of changes in the age-depth curve of our core differs from these other records which, importantly, also differ from each other.

Thus, the effect of climate change on the PMFB peatland is not straightforward. Climate can affect both litter production and decomposition in ways that may differ depending on site floristics, topography, and hydrology but are not yet well understood in this region. Future peat carbon modelling studies (Wang et al., 2018; Young et al., 2026) will need to consider the apparent variation in peat accumulation histories within this region.

5.4. Re-establishment of open vegetation and *Mauritiella* swamp forest, c. 1610–770 cal yr B.P. (Zones 3–4)

A return to more open conditions, a Cyperaceae-dominated peat-forming fen, occurred c. 1610–1360 cal yr B.P. at Nueva York. The increase in herbaceous taxa, accompanied by an expansion of *Cecropia*, indicates a substantial reduction in canopy cover. The DCA scores

(Fig. 4) superficially suggest a return to vegetation like those of the Cyperaceae-dominated fen phase c. 7500–6500 cal yr B.P. The herbaceous assemblage at this time, however, was different and less diverse, with less Asteraceae and Piperaceae and more Cyperaceae, Poaceae, and *Eichhornia*. *Eichhornia* frequently forms vegetation mats in lakes, streams, and backwater areas (Jafari, 2010; Villamagna and Murphy, 2010). The palynology thus suggests the development of a pool at the site, possibly an open herbaceous peatland, with floating mat and/or fen vegetation. There is no detectable evidence for localized human impact: charcoal abundance is low and remains low throughout the remainder of the sequence.

The change at Nueva York has parallels in similar re-expansions of Cyperaceae at Quistococha and a substantial expansion of Cyperaceae and the aquatic plant *Pistia stratiotes* at San Jorge, both occurring during the second millennium BP (Fig. 7) (Roucoux et al., 2013; Kelly et al., 2017). An increase in Myrtaceae c. 1800–1610 cal yr B.P. occurred at both Nueva York and Quistococha, preceding the change to a Cyperaceae fen/floating mat. Peat from this interval is effectively missing from Aucayacu (Swindles et al., 2018).

The phase of open vegetation c. 1610–1360 cal yr B.P. ended abruptly at Nueva York. The site did not re-establish as a hardwood

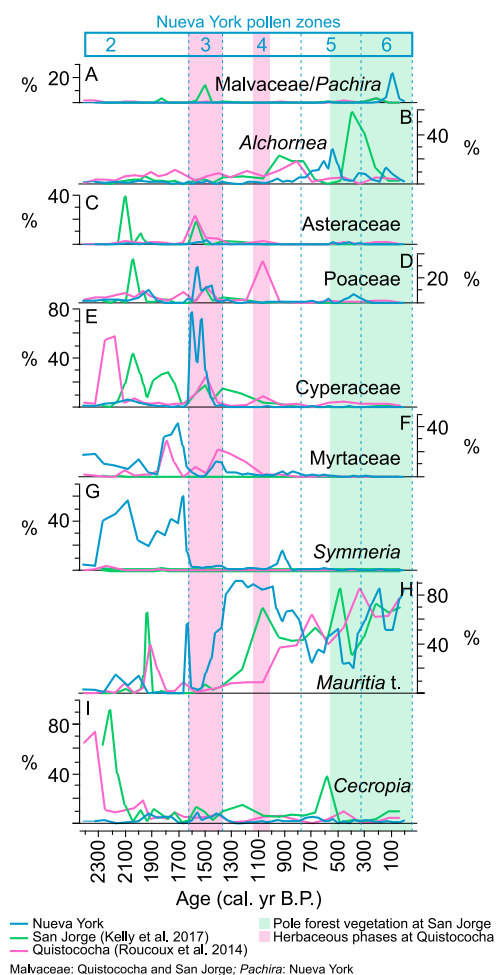


Fig. 7. Diagram comparing key pollen taxa from Nueva York (blue line), San Jorge (green line; Kelly et al. (2017)), and Quistococha (pink line; Roucoux et al. (2013)), Peru, against age (cal yr B.P.) focusing on the past 2400 years. From the top: (A) Malvaceae/*Pachira*; (B) *Alchornea*; (C) Asteraceae; (D) Poaceae; (E) Cyperaceae; (F) Myrtaceae; (G) *Symmeria*, (H) *Mauritia* t., and (I) *Cecropia*. Shaded pink area denotes herbaceous phases seen at Quistococha and shaded green area denotes the shift to pole forest vegetation at San Jorge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

swamp but instead succeeded to a *Mauritiella* swamp with *Symmeria* and Myrtaceae, effectively repeating the transition seen at c. 6360–5000 cal yr B.P. A very similar change, again repeating an earlier transition, was seen at Quistococha around 1000 cal yr B.P. (Roucoux et al., 2013).

These between-site similarities could be taken to indicate a common climatic control but given the uncertainties in temporal precision of correlation between sites, a safer interim conclusion is that the development of pools lasting up to a few centuries, with varying kinds of vegetation, is now a common feature of PMFB palaeoecological records. Possibly analogous peatland ponds are widespread throughout the PMFB today and deserve further study to establish how they form.

5.5. Palm swamp and the establishment of pole forest vegetation, 770 cal yr B.P.–present (Zones 5–6)

Grain size measurements suggest that *Mauritiella armata* gave way to *Mauritia flexuosa* at 770 cal yr B.P. (Zone 5), indicating reduced frequency and/or depth of flooding at the site, accompanied by increases in *Alchornea*, Combretaceae/Melastomataceae, *Lueheopsis*, *Tabebuia*, *Euterpe*, *Symphonia*, and Morphotype 181 (Supplementary Material Fig. S-4). *Mauritia flexuosa* today dominates peat-forming ecosystems across the PMFB, including open peatlands, palm swamps, and pole forests, so it is striking that its expansion occurs so late at Nueva York. In four out of the five published PMFB swamp forest sequences where grain sizes have been measured (Kelly et al., 2017; Kelly et al., 2020), the main expansion of *Mauritia* follows *Mauritiella* as seen at our site. The *Mauritia*-dominated assemblages in Zone 5, however, are accompanied by increases in Poaceae, Asteraceae, and *Alchornea*, indicating some openness at the site, i.e. a broken canopy, which is not typical of pollen assemblages from other (minerotrophic) palm swamps in the region (Draper, 2015; Kelly et al., 2020) but shares similarities with the open peatland San Roque, though probably with a less degree of openness (Sassoon et al., 2024).

As before, the independent evidence for a climatic driver is equivocal. The two δD curves from our core show different directions of change, suggesting that they are unreliable as climate proxies (Fig. 6). Stable isotope records from Lake Pumacocha (Bird et al., 2011) and Palestina Cave (400 km WSW of Nueva York; Apaestegui et al., 2014) are highly congruent with each other and with other, more distant Andean records from around 1100 cal yr B.P. and are therefore more likely to be reliable indicators of regional climate trends despite their distance from Nueva York. In the last c. 700 years both show a small and gradual shift to wetter conditions, peaking around 500 cal yr B.P., then gradual drying after c. 300 cal yr B.P. (Fig. 6). There is little obvious correlation with our pollen data, although it is plausible that these changes in wetness could account for the low peak in Poaceae, via increased flooding, in the middle of Zone 6. Similarly, there is no direct evidence that human action was involved in the vegetation changes in Zone 6: charcoal is all but absent and there are no cultigens in the pollen record. While some form of allogenic (climatic or human) disturbance thus cannot be ruled out, the most parsimonious interpretation is that the vegetation development during Zone 6 was dominated by an endogenic trend towards ombrotrophy (i.e. dependent on precipitation for their water and nutrient supply).

Today, the vegetation at Nueva York is a thin-stemmed ‘peatland pole forest’ (sensu Draper et al., 2018; Honorio Coronado et al., 2021) dominated by *Pachira*, *Platycarpum*, and *Hevea*, which jointly make up half of the stems at the site (Table 1), but which are strongly under-represented in pollen assemblages (Kelly et al., 2017). In the most recent pollen sample, these genera combined represent 1.7% of the pollen sum. They are numerically overshadowed by *Mauritia* t. which reaches 84% in the top pollen sample, versus only 9% of stems in the census plot. Hence, even a small abundance of these pole forest ‘indicator taxa’ likely indicates local pole forest establishment (Kelly et al., 2017).

The pole forest at Nueva York appears to be only a few centuries old, as pole forest indicator taxa only are present from c. 770 cal yr B.P.

(Zone 5); with consistent occurrence after c. 320 cal yr B.P. For comparison, the pole forest at San Jorge has a maximum age of 200–150 cal yr B.P. (Kelly et al., 2017). The gradual increase of pole forest indicator taxa at Nueva York supports the view that pole forest vegetation succeeded gradually from the earlier palm swamp, probably following an endogenic hydrosere (cf. Läheteoja et al., 2009; Läheteoja et al., 2012; Draper et al., 2018) as the peat mass built upwards beyond the regular reach of minerotrophic groundwater or riverine flooding, i.e. a form of fen–bog transition.

6. Conclusions

The 7800 year-long palaeoecological record from Nueva York, Peru, is among the oldest from the PMFB peatlands and one of only three from a pole forest peatland. Our record supports the emerging pattern of vegetation succession in PMFB peatlands, where site terrestrialization started from an open-water setting, via Cyperaceae fen and mixed hardwood swamp forest, to palm swamp, and ultimately to peatland pole forest (cf. Roucoux et al., 2013; Kelly et al., 2020). The endogenic processes (basin infilling, tendency towards ombrotrophy) were, however, deflected by ‘reversals’, suggesting that allogenic processes (river channel migration, climate change, and possibly human impact) affected the site.

Apparent carbon accumulation rates in the top 4 m vary by a factor of two with no indication of any hiatus in the last 2300 years, showing similarities with some PMFB records but contrasting with others (Roucoux et al., 2013; Kelly et al., 2017; Swindles et al., 2018; Kelly et al., 2020). The Nueva York record indicates that any link between climatic change and peat carbon accumulation is likely to vary from site to site, making it difficult to predict response of the region to 21st century climatic change. Further work is needed to better understand the processes that link climate and peat carbon accumulation.

The vegetation at Nueva York changed substantially within the past few centuries, with taxa typical of peatland pole forest increasing gradually over the last c. 770 years and an establishment during the last 320 years. The record adds to the growing body of evidence that the PMFB landscape is dynamic, a constantly shifting mosaic of different vegetation types on decadal to centennial timescales. Conservation and management of the region will need to take this apparently natural dynamism into account, conceptualising the wetlands as an interconnected and ever-changing landscape in which our aim should be to protect the integrity of the underlying successional processes, rather than merely to preserve the present state of the vegetation.

Authors' contribution

CMÅ, AB, GCD, PG, WH, and KHR performed research. CMÅ analysed data. CMÅ, ITL, KHR wrote the manuscript. TRB, AB, GCD, JAP, FCD, GF, PG, AH, WH, ENHC, TJK, ETAM, DS, and MW contributed to writing the manuscript. ITL, TRB, ENHC, ETAM, KHR, and MW conceived the project. GCD, JAP, and GF conducted field work.

Data archiving

The datasets produced from this study are available to the public through the UKCEH Environmental Information Data Centre, Ecosystem productivity data from wetland sites in the Pastaza-Marañón Basin, Amazonian Peru, 2018–2020 - EIDC.

CRedit authorship contribution statement

Christine M. Åkesson: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Katherine H. Roucoux:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Formal analysis,

Conceptualization. **Arnoud Boom**: Writing – review & editing, Methodology, Formal analysis. **Greta C. Dargie**: Writing – review & editing, Methodology, Investigation, Formal analysis. **Jhon del Aguila-Pasquel**: Writing – review & editing, Methodology, Formal analysis. **Gerardo Flores**: Writing – review & editing, Methodology, Formal analysis. **Pauline Gulliver**: Writing – review & editing, Methodology, Formal analysis. **William Hiles**: Writing – review & editing, Methodology, Formal analysis. **Timothy R. Baker**: Writing – review & editing, Funding acquisition, Conceptualization. **Frederick C. Draper**: Writing – review & editing. **Adam Hastie**: Writing – review & editing. **Eurídice N. Honório Coronado**: Writing – review & editing, Funding acquisition, Conceptualization. **Thomas J. Kelly**: Writing – review & editing. **Edward T.A. Mitchard**: Writing – review & editing, Funding acquisition, Conceptualization. **Dael Sassoon**: Writing – review & editing. **Mathew Williams**: Writing – review & editing, Funding acquisition, Conceptualization. **Ian T. Lawson**: Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We would like to offer our gratitude to the people and government of Peru, especially the community of Nueva York, for their permission to access their lands and for making this study possible. We thank NERC (ref. NE/R000751/1) for the financial support of this research. Radiocarbon analysis was supported by the NERC Radiocarbon Facility NRCF010001 (allocations 2121.0818 and 2420.0421). AH acknowledges the following funding: Charles University (PRIMUS/23/SCI/013), Charles University Research Centre program (UNCE/24/SCI/006) and the OP JAK programme ‘Natural and anthropogenic geohazards’ (CZ.02.01.01/00/22_008/0004605). Julio Igarica is thanked for his assistance in the field, and the Instituto de Investigaciones de la Amazonian Peruana is thanked for logistical support. We would also like to thank Genna Tyrrell for laboratory support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.palaeo.2026.114162>.

Data availability

The authors confirm that all data necessary for supporting the scientific findings of this paper have been provided.

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